COLOR MEASUREMENT

And Its Application to the Grading of Agricultural Products

A HANDBOOK ON THE METHOD OF DISK COLORIMETRY

By
DOROTHY NICKERSON, Color Technologist,
Production and Marketing Administration

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CONTENTS

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By DOROTHY NICKERSON, *color technologist*

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INTRODUCTION

In the 16 years since publication of the disk method for determining the color of agricultural products (*48*),[1] the science of colorimetry has made great strides. In 1931 at the Cambridge (England) meeting of the International Commission on Illumination,[2] certain conventions and standards for use in colorimetry were adopted (*9, pp. 19-29; 68, 35, 43*) that have since been put to practical use throughout the world (*76*). This, and the development of instruments for the rapid and fundamental measurement (*27, 18, 75*) of color, have stimulated color work and have made it possible to coordinate work done under a variety of conditions and on a variety of instruments, for practically all results may now be reduced to standard I. C. I. data. The (x, y)—coordinates of the I. C. I. system provide a common language for translation of color work of practically all types and kinds. Although the I. C. I. system may not be perfect, it does provide a common language for use in colorimetry, and that alone is important.

This publication is intended as a general introduction to color measurement for those interested in the subject as it relates to grading work, and it is also intended as a handbook on the method of disk colorimetry. References to bibliographical material are used freely in order that students who care to do so may become familiar with a general background of authoritative information on problems involving color measurement and specification.

COLOR-GRADING PROBLEMS

Grades formulated in the United States Department of Agriculture for many products include reference to color, and when standards for these grades are developed, color must be considered. Much of the grading work is done by inspectors or graders who carry in their minds a conception of standards for the product with which they are concerned. Among these products are cotton, hay, butter, cheese, eggs, fruits and vegetables (fresh, canned, frozen, and dried), honey, tobacco, cereal grains, meats, and rosin.[3]

For some of these products, standards are prepared in physical form; for some, they are set in terms of measurements for selected quality factors; for others, they are set by word descriptions. When color is a part of a standard, it is generally assumed that daylight color is referred to. In products such as cotton, hay, and tobacco, daylight color is highly important. For cotton it is so important that special skylights have been developed for cotton classing rooms so that in classification work the best type of natural daylight may be provided, whether classification is made by actual comparison with standards, or by comparison with a memory standard. In recent years artificial daylighting studies[4] conducted in the United States Department of Agriculture (*53, 54, 56*) have provided specifications that have been met by artificial daylighting units now installed in many cotton classing rooms. Smaller units of this same type of daylighting are used in the inspection of flour and grain, as in macaroni and bread tests, and in the grading of processed foods.

Various commodities have a distinctive color terminology and an important and common question that arises is that of relating color standards to terms used in commercial practice.

Cotton, for example, is variously described in the trade as creamy, bloomy, bright, gray, dull, spotted, tinged, and stained. The official standards include definite color differences within and between grades of White, Extra White, Gray, Spotted, Tinged, and Yellow Stained cottons.

In the hay trade, color may be called natural green, pea green, bright natural color, brown, tobacco brown, good color, fair color, poor color, bleached, stained, and weathered. The official hay standards use color as a grade requirement in terms of "percent green color," a

[1] Italic numbers in parentheses refer to Literature Cited, pp. 61-63.
[2] Usually abbreviated as I.C.I. in American publications; C.I.E. is also used in British publications to refer to the French translation of Commission Internationale de l'Eclairage. The original proceedings were published in French (*9, pp. 19-29*).

[3] Specifications of official standards for agricultural products are available in the United States Department of Agriculture. In general, the specifications for standards are printed in Service and Regulatory Announcements (S.R.A.'s) and handbooks, or are issued in processed form.
[4] Discussed on pp. 53-59.

method which makes it possible to use one comprehensive term for nearly all descriptive trade terms. The percentage of green color is in turn measured and correlated with Munsell hue, and although the same hue may be a different "percent green" for timothy hay than for alfalfa or clover hay, this measurement provides a real basis for standardization.

For butter, there is a different terminology. The color may be described as very light, light, medium, high, and abnormally high (rated as a defect). Other defects are specked, wavy, mottled, streaked, and so on. Cheese may be uncolored, medium-colored, uniform, high-colored, seamy, acid-cut, mottled, wavy, badly faded. Eggs may be stained; their yolks may vary from a deep reddish brown to a pale yellow.

The terms water white, extra white, white, extra light amber, light amber, and amber are used in official grades for honey.

In descriptions of the official standards for flue-cured tobacco, the colors are designated by letters: L is for lemon; F for orange; D for red or mahogany; G for green; and M for mixed.

Grains are described in terms peculiar to the practices in grading them, and many of the color terms used in the grain trade are now incorporated as class and grade requirements in the official grain standards: Red, white, yellow, amber, pink, dark, light, gray, black, good color, bleached, bright, stained, weathered, and discolored.

The lean of beef has a color terminology: Dark pink, very light cherry red, light cherry red, slightly dark cherry red, moderately dark red, dark red, and very dark red. Beef fat may be white, creamy white, creamy, slightly yellow, yellow, very yellow, or fiery.

Fruits and vegetables have their distinctive color terminology. This is particularly true of the citrus fruits which are generally described in terms of "percent color."

Canned fruits and vegetables are quite generally graded on the basis of U. S. grades, and color is a factor that frequently appears on the score cards for grading these products.

It is clear that even when a product has been measured or standardized for color, the problem still remains of establishing a simple and satisfactory conversion into current trade terms. For, whether current trade terms are to be used or not, it is absolutely necessary that such terms be understood in terms of some series of color standards. The laboratory worker who measures the color of any product cannot be of practical use until he and the practical grader can discuss their mutual color problems in a common language. Together they may solve many color problems, but first there must be a basis for common understanding.[5]

COLOR CHARTS IN GRADING WORK

For some few grading problems, color charts may provide a satisfactory answer. If a standard that actually matches a color chip on a chart can be established, then charts can be used; or, in specifying a general approximation to the required color, charts may be useful. Since for some problems color charts are still in wide use, the most important of them are briefly described.

Ridgway charts (*66*), first developed in 1886 and enlarged in 1912 by Robert Ridgway of the United States Biological Survey, contain 1,113 colors, 36 hues reduced by regular proportions of white, gray, and black to give systematic groupings. The first group of charts represents what Ridgway calls "tints" and "shades" of his 36 full colors, and the groups that follow represent "tints" and "shades" of "broken colors," the full colors being reduced with a definite amount of neutral gray. To each of the colors on his charts, Ridgway gave a name, in order that meanings might be established for color names used in the natural sciences.

The *Maerz and Paul Dictionary of Color* (*42*) published in 1930 contains 7,056 colors, on 56 charts, with a very useful text of 73 pages. It is the best authority available for use as a dictionary of color names, that having been the purpose for which it was published. To arrive at a series of charts by which the meaning of color names could be illustrated, the authors selected their arrangement after practical tests and had the charts printed before any matching or technical measurements were made. The order of hue presentation follows that of the spectrum, the charts being divided into seven main groups: Red to orange; orange to yellow; yellow to green; green to blue-green; blue-green to blue; blue to red; purple to red. On each plate, the end colors grade by small degrees from the full or reduced hues into each other in one direction and into white or gray in the other. Each hue group is presented in eight successive plates, the first in full chroma printed on white, the second printed over a light gray, the third over a darker gray and so on until the colors approach black. The size of most samples is about $\frac{1}{2}$ by $\frac{11}{16}$ inch. After the charts were printed, the color most nearly representing each color name was selected and marked with that name.

In setting color standards for canned fruits and vegetables[3] in the United States Department of Agriculture, use has been made of the color charts of Maerz and Paul, not because other methods might not be preferable if they could be made practical, but because for color-matching purposes this dictionary has in it the widest number of colors now available. One disadvantage is that the colors of neighboring samples in some places on the charts are very close, so close that they appear to be the same color; in other places there are wide differences between the colors of neighboring samples. Another disadvantage is that the charts are printed and cannot therefore be accurately reproduced in future editions. In 1939 and 1940, copies of many of the border-line colors for grades of canned products were reproduced[6] from specifications made by reference to the Maerz and Paul charts.

Munsell charts may be obtained in a standard series of 20 or 40 hues, each graded through many steps of value

[5] Color-vision deficiencies are discussed in the latter part of this publication. References are given to a number of color-vision tests, including one for color aptitude.

[6] Some of these can be found in Food Industries II: 381-384, 497-498, 554A-554D, 619-624 (color plates on pages 382, 498, 554C, 623, 624), and 55-58 (color plates on pages 56 and 57).

and chroma, a total of 421 colors in the standard 20-hue series, or 982 colors in the 40-hue series, with several hundred more special Munsell colors available. Since the Munsell system is described in detail later in this publication, it is sufficient here to note that in the standard library-size edition of the Book of Color (*45*) each color chip is repeated on several series of charts in order to show the same colors in different relationships, the charts in this book being large and particularly useful for teaching and demonstrating the Munsell notation. The pocket-size edition of the Book of Color, recommended for most laboratory and matching purposes, contains only one chip of each color. Since this edition includes no repetitions (it is obtainable in 20 or 40 hues), it is more compact and becomes a very convenient series to use, especially since the charts (3¾ by 6¾ inches) are mounted in a ring binder and are removable. Samples on these charts are ½ by ⅝ inch. For a still less expensive series of Munsell charts, the Student Edition provides the answer. In this series the color chips are supplied in separate envelopes with blank charts ready to be mounted.

The Munsell charts, in 40 hues, contain 982 colors in comparison with 7,056 colors in the Maerz and Paul Color Dictionary. The Munsell charts, however, have an advantage. Although through their use a match may not be made as readily to a given sample, it is possible to make interpolations to any degree of fineness that is desired since the Munsell system of notation is devised on a psychological system of visually equal steps for scales of the three color attributes: Hue, value, and chroma. Thus the color chips are spread over the entire color solid, instead of being concentrated in certain areas.

In the color naming of drugs and pharmaceuticals, a method was devised (*38*) of using masks for making interpolations between color chips on the Munsell color charts. On a check test made with two observers in connection with a soil-color study (*65*), results showed an average difference of 0.6 step for hue, 0.2 for value, and 0.3 for chroma (out of 100 steps for hue, 10 steps for value and chroma). This method, which has wide possibilities for use in color work in which there is not the time nor the equipment for color measurement by instruments, is described later in this publication. In a sense, the use of a mask in color matching may be said to provide the very simplest form of color instrument. It is the first departure toward color measurement that can be made easily when it is first discovered that color charts are not sufficiently flexible for extended use in grading work.

There are other charts, some of them widely used in certain fields, that do not have particularly wide use or application to agricultural grading problems. Chief among them may be named the recent American publication of Ostwald charts (*33, 22, 15*); the standard cards of The Textile Color Card Association of the United States, Inc.; standard cards of the British Colour Council for textiles; the Repertoire de Couleurs and the Horticultural Colour Chart in current use in horticulture and related fields. There is also a group of about 150 color samples in unabridged editions of Webster's New International Dictionary published since the 1935 revision.

Specification of color in terms of charts becomes increasingly useful as the chart itself becomes widely known, or as conversion tables become available that allow the colors of one chart to be specified in terms of another. Much standardization has been done in recent years that has laid the basis for conversions of this sort. Although as yet conversions have been completely published for only the Munsell and Ostwald charts, results for the Textile Color Card Association standards will soon be published, and work is under way on the charts of Ridgway, and Maerz and Paul so that most of them will be available, many in Munsell terms.

TRANSPARENT-COLOR STANDARDS IN GRADING WORK

For standardizing transparent products, such as honey and rosin, it is sometimes convenient to make use of special wedges of glass, or to use Lovibond glasses or Arny solutions. For a few products (honey, milk, etc.) glass wedges or liquid standards can be prepared. For others, standards may be in terms of Lovibond glasses, or combinations of them. Many oils, cottonseed and soybean among them, are graded in this way.

In practically all chemical laboratories color is employed as an indication of chemical constitution, and samples are specified by comparison with standard depths and concentrations of known materials. The instruments, which generally hold test tubes of the known and unknown materials so that they may be seen for comparative purposes, are often called colorimeters. A preferable name would be color comparators.

The Lovibond system consists of three series of glasses: Red, yellow, and blue. The scale unit of each series is arbitrary but three units are related in such a way that a subtractive combination, in daylight, of one unit of each scale results in a neutral. The many glasses in each series are marked by the number of unit glasses to which each is the equivalent. These glasses are made in England. Originally they were made to aid in the color control of beer but they are now used for many other purposes—in this country chiefly for the grading of vegetable oils. Much standardization of these glasses has been done for the oil chemists at the National Bureau of Standards (*19, 20, 29*), and by the Electrical Testing Laboratories. Tintometer, Ltd., manufacturers of the glasses, have cooperated in the test work, and have published several reports in England (*73, 14*). Recently a network for I. C. I. "C" illuminant based on 9 yellow and 28 red glasses has been prepared by Detwiler.[7]

Arny Solutions consist of a group of solutions whose concentrations are adjusted to produce a color match, the required concentrations providing a specification of the color. The group of solutions most often used consists of half-normal aqueous solution of cobalt chloride (red), ferric chloride (yellow), and copper sulfate (blue) with 1 percent hydrochloric acid. From this group all colors except deep blue and deep red are produced.

[7] S. B. Detwiler, Jr., Bureau of Agricultural and Industrial Chemistry, United States Department of Agriculture, unpublished manuscript.

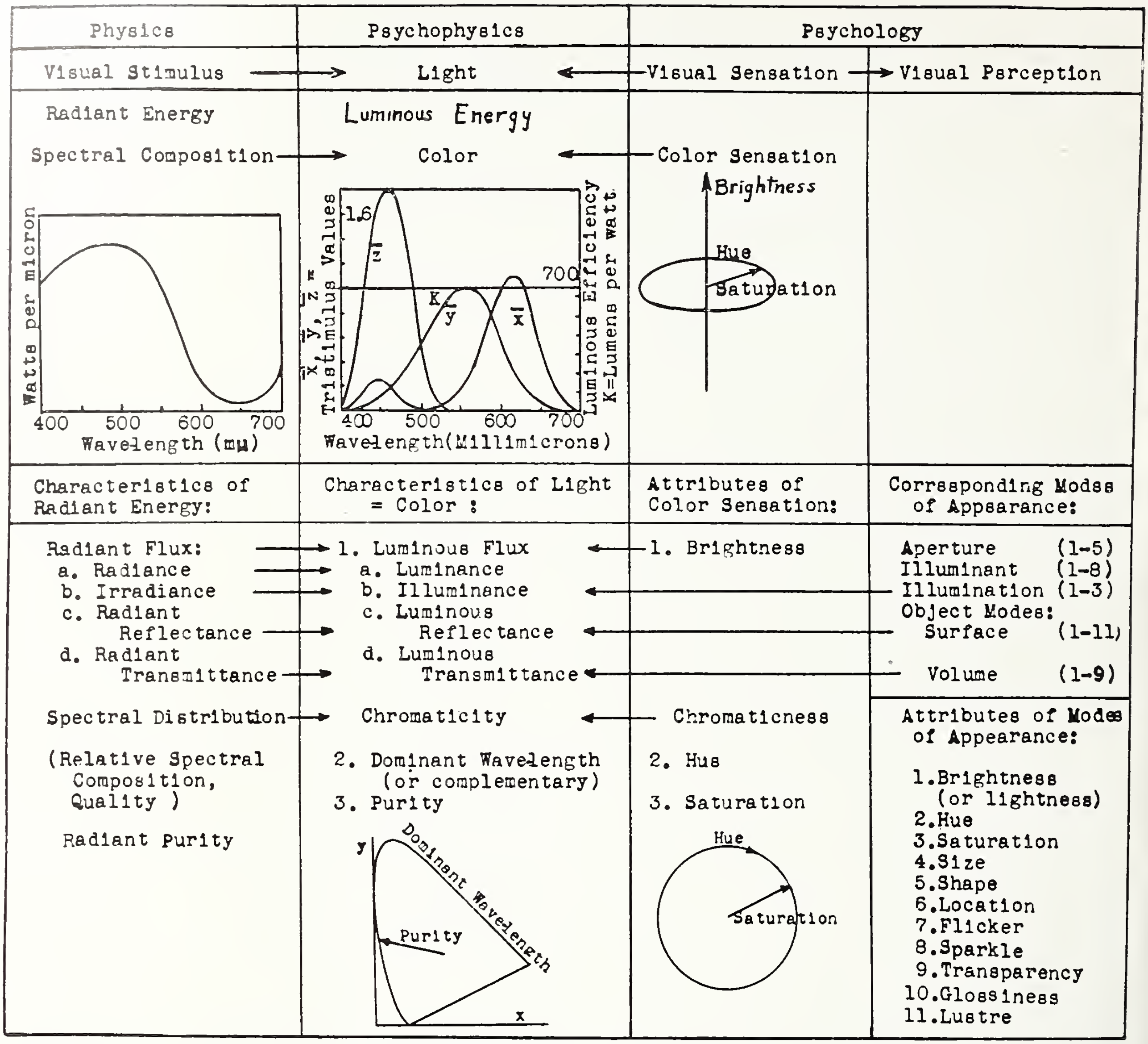

FIGURE 1.—Correspondence and terminology of the several attributes of radiant energy, color, and color sensation, all of which are involved in color measurement. (This chart appears, figure 3, in a report by the Colorimetry Committee of the Optical Society of America (*63*).)

The group may be supplemented by other combinations (*3, 4, 5*).[8] In the eleventh edition of the U. S. Pharmacopoeia, Arny solutions are used as standards for color of cod liver oil and in carbonization tests with sulfuric acid for 28 compounds.

STANDARDS NEED MEASURING

When color is involved as a part of a standard and any real study of the relation between the colors of sample and standard is made, specifications in terms of color chips on a chart are generally not sufficient. Then it becomes necessary to interpolate between chips or to resort to some means of color measurement. More often than not, color measurement is necessary only for specifying the standard with which samples are compared; but it may also be used for measuring individual samples, particularly for border-line or disputed cases. Thus, even when standards are prepared in the laboratory by use of color measurement, often it is not necessary for inspectors or graders who use those standards to have knowledge of technical color work in order to apply the standards. However, since several distinctly different methods may be applied in problems of color measurement, certain fundamental ideas will be considered before the discussion is narrowed to particular methods.

[8] Recently Kelly has published a revised method with Munsell and ISCC-NBS color names for matching fluids: KELLY, K. L.. A NEW SYSTEM OF COLOR MATCHING FLUIDS. Amer. Pharm. Assoc. Jour. 34: 59-63. 1945.

SEVERAL METHODS OF EXPRESSING RESULTS OF COLOR MEASUREMENT

No problem can be discussed adequately unless the terminology used is understood by all who take part. Color is no exception, but to the layman it is so much a part of his everyday life that the importance of standard terminology is seldom considered, except when he wishes to name what Robert Louis Stevenson has called an "exact shade."

There are two distinctly different methods for measuring color. By one, the color may be measured indirectly by specifying the stimulus, completely or partially, in terms of reflectance or transmittance at each wave length in the visible spectrum (spectrophotometry) ; by the other, color may be matched by the use of secondary standards, such as filters and disks (colorimetry). In both cases, if the measurement is to be reported in terms other than those of the instrument itself, it can be expressed either in terms of psychophysical or psychological color attributes.

Any real understanding of the subject of color must take into consideration several different, but related, aspects of the subject. A physicist is interested in the properties of the stimulus, and in the eye as far as the physical properties of the visual mechanism are concerned. A psychologist is interested in the subjective aspects of color experience, what the color looks like, and how its appearance may be described in terms of equal-color steps. Before the two can have a common meeting ground, a relation between instrumental measurement (physical) and color appearance (psychological) must be found. That relation is found in what are called psychophysical studies. Figure 1, taken from a discussion of the concept of color (*63*) by the Colorimetry Committee of the Optical Society of America, is the clearest portrayal that colorimetry's experts can make at the present time to show the correspondence and terminology of the several attributes of radiant energy (physics), light (psychophysics), and visual sensation and perception (psychology), all of which are involved in color measurement.

Physical studies of color include the use of a spectrophotometer. Fundamental studies of color grading work should include enough spectrophotometric data on the product under consideration to give the investigator detailed knowledge of the spectral reflectance or transmittance properties of his product. Yet, in much grading work those who set the standards need not know what a spectrophotometric curve of their product looks like. This is particularly true of standards work with agricultural products because, in the usual case, standards are set up in terms of the product itself, and the range of spectrophotometric differences in samples of high to low grades follows a similar pattern, or a family of curves. When dealing with such products as pigments, dyes, printing inks, the reverse may be true, for it may be more important to know the spectral reflectance or transmittance characteristics of colorants than to know what they look like. Figure 2 shows typical

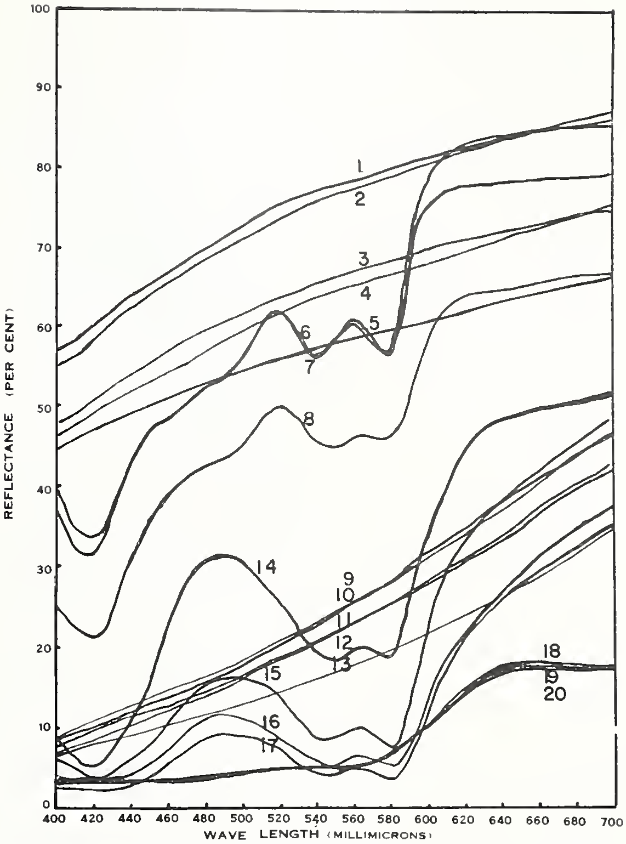

FIGURE 2.—Typical spectrophotometric curves of a number of agricultural products: 1-5, cotton; 6-8, fresh cut beef fat; 9-13, wheat kernels; 14, fresh cut pork; 15-17, fresh cut beef; 18-20, tomato pulp.

spectrophotometric curves of a number of agricultural products.

Entirely the opposite of physical studies, are the color studies that are concerned only with the color appearance of a group of samples. When slabs of meat are laid out, or stalks of tobacco, or pats of butter, and color standards are set by visual estimates, the colorimetry involved may be called psychological.

Only when a means is found for measuring, either directly in physical terms or indirectly by means of secondary standards, the standards thus established, can it be said that a color grading problem is satisfactorily completed. For no matter how well a series of visually selected standards may first serve the purpose, such standards cannot be remembered accurately, and if represented in material form they may deteriorate or be destroyed. It seems logical, therefore, to agree that satisfactory color work in setting standards must be done on a psychophysical basis, that is, by measuring standards that are *visually* satisfactory by means of physical *instruments* in terms of data derived from the use of both methods. Three methods of notation are widely used for doing this.

I.C.I. Method of Color Notation

In the I. C. I. method of color notation, results of instrument measurements are reduced directly into terms of the standard observer and coordinate system of colorimetry adopted (*9, pp. 219-20*) in 1931 by the International Commission on Illumination. The data are expressed as the absolute (X, Y, Z) and fractional (x, y, z) amounts of three imaginary red, green, and blue lights necessary for an imaginary standard observer to match a given sample under a given illuminant. Since the Y function of the I. C. I. standard observer is set to carry all the luminosity, it is usual for the data to be expressed as Y for luminous reflectance, and as (x, y) for plotting on an (x, y)-mixture diagram. Such a diagram is illustrated in figure 3, in which the curved line

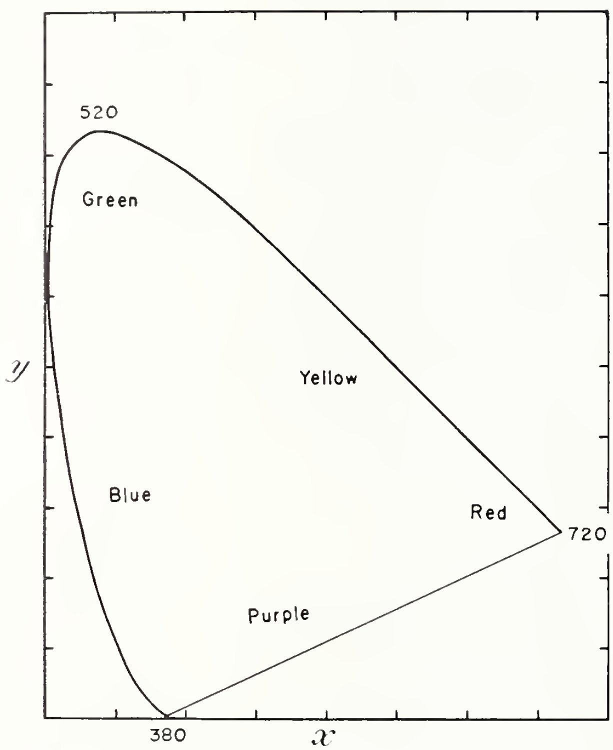

FIGURE 3.—I.C.I. (x, y)-color mixture diagram, with spectrum locus, reds through yellows, greens, and blues, from 720 millimicrons to 380 millimicrons. The straight line connecting the ends of the spectrum encloses the region of purple and red-purple colors not represented in the spectrum.

represents the spectrum locus, from the far red at 720 millimicrons to the far blue at 380 millimicrons. *Color mixtures lie on straight lines on this diagram.* An illuminant of some sort must be assumed before I. C. I. data can be calculated, and the illuminant is thereafter the central reference point for the data. The spacing on the diagram has little or no relation to equal color-sense intervals.

Homogeneous-Heterogeneous Method of Color Notation

The homogeneous-heterogeneous or dominant wave length-purity method of color notation is one in which results of color measurements are reduced directly[9]—or indirectly through conversion from I. C. I. notation—into terms of the homogeneous-heterogeneous system in which a mixture is made or calculated for the amount of spectrum light of a homogeneous nature (single wave lengths) and the amount of heterogeneous (neutral) light needed to match a given sample. Luminous reflectance or transmittance is separately measured. The wave length of the homogeneous light needed to match the sample is called the dominant wave length of the sample, and the purity (excitation purity) is the relative amount of neutral light needed to desaturate the homogeneous spectrum light to match the sample under a chosen illuminant. The spectrum locus is plotted on the I. C. I. (x, y)-diagram in figure 3, and in a similar figure lines of dominant wave length may be drawn from the spectrum locus to a point representing a chosen illuminant. (I. C. I. standard illuminants are A, representative of a gas-filled incandescent lamp operating at a color temperature of 2848° K; B, a representation of noon sunlight at approximately 4800° K; and C, a representation of average daylight at approximately 6700° K.) Lines of constant purity may be drawn on such a diagram, 100 percent being the purity at the spectrum locus, 0 percent that of the illuminant used as the reference point. It should be noted that a given (x, y)-point on such diagrams must refer to the illuminant for which each is calculated. The dominant wave length and purity of $x = 0.41$, $y = 0.40$, when referred to illuminant A is a blue approximately 492 millimicrons in dominant wave length, and 10 percent purity; when referred to illuminant C the same (x, y)-point represents a yellow that is 580 millimicrons in dominant wave length, and 50 percent purity. Luminous reflectance or transmittance in this system is separately specified; the dominant wave length and purity remain the same for a given (x, y)-point regardless of whether the luminous reflectance indicates a light or a dark color.

Direct methods of measuring dominant wave length and purity are usually not satisfactory. The reason is that the two fields to be compared are spectrally very different, therefore differences in color vision between observers cause wide differences in results. Indirect methods, however, have been widely used for illuminant C since the publication in 1936 (*43*) of large-scale charts for converting I. C. I. (x, y)-data to dominant wave length and purity.

[9] A method of direct measurement by use of the monochromatic colorimeter, developed at the National Bureau of Standards in 1923, is described by I. G. Priest: APPARATUS FOR THE DETERMINATION OF COLOR IN TERMS OF DOMINANT WAVE LENGTH, PURITY, AND BRIGHTNESS. (Abstract) Optical Soc. Amer. Jour. & Rev. Sci. Instr. 8, 28. 1924.

Munsell Method of Color Notation

The Munsell method of color notation[10] developed in the early part of this century (*44, 55*) may be used directly if measurements are made by comparison to Munsell charts or it may be used indirectly by converting I. C. I. notations into Munsell notations. In the Munsell notation, color is expressed in units of visual difference of the three psychological attributes: Hue, lightness, and saturation.[11] By this method results of color measurements are expressed in terms of *color order* rather than *color mixture,* and allow an interpretation of results directly in terms of the visual qualities known in the Munsell system as hue, value, and chroma. Because the Munsell concepts and notation are used so much in this publication, they are described in detail.

Munsell hue is that attribute of certain colors in respect to which they differ characteristically from a gray of the same lightness and which permits them to be classed as reds, yellows, greens, blues, or purples. The Munsell hue circuit is divided into 10 major hues, as follows:

R:	red	BG:	blue green
YR:	yellow red	B:	blue
Y:	yellow	PB:	purple blue
GY:	green yellow	P:	purple
G:	green	RP:	red purple

These are shown in diagram form in figure 4. Each of

[10] Developed by A. H. Munsell, artist and art educator of Boston, Mass., under whose direction the earliest Munsell charts were developed. In 1918, prior to his death, the Munsell Color Co. was formed to carry on the work of providing charts and other educational supplies for teaching the Munsell system. This company had become essentially a scientific organization, and in 1942 the Munsell family, which had supported its activities since 1918, created the Munsell Color Foundation and turned the company over to it. This foundation is a nonprofit organization whose purpose as quoted from its charter is "to further the scientific and practical advancement of color knowledge and in particular knowledge relating to standardization, nomenclature, and specification of color, and to promote the practical application of these results to color problems arising in science, art, and industry." The Director of the National Bureau of Standards and the Inter-Society Color Council each appoints one of the several trustees. The others are well known in the color field. In 1945 the trustees are Deane B. Judd, Dorothy Nickerson, Blanche R. Bellamy, A. E. O. Munsell, I. H. Godlove, L. A. Jones, Royal B. Farnum (succeeding Arthur S. Allen, deceased 1944).

[11] These terms are used in the 1943 report of the Colorimetry Committee of the Optical Society of America, and supersede the terms used in the 1921 O.S.A. report and in the USDA publication (*48*), particularly in the substitution of the terms brightness and lightness for the term "brilliance." The substitution is a good one.

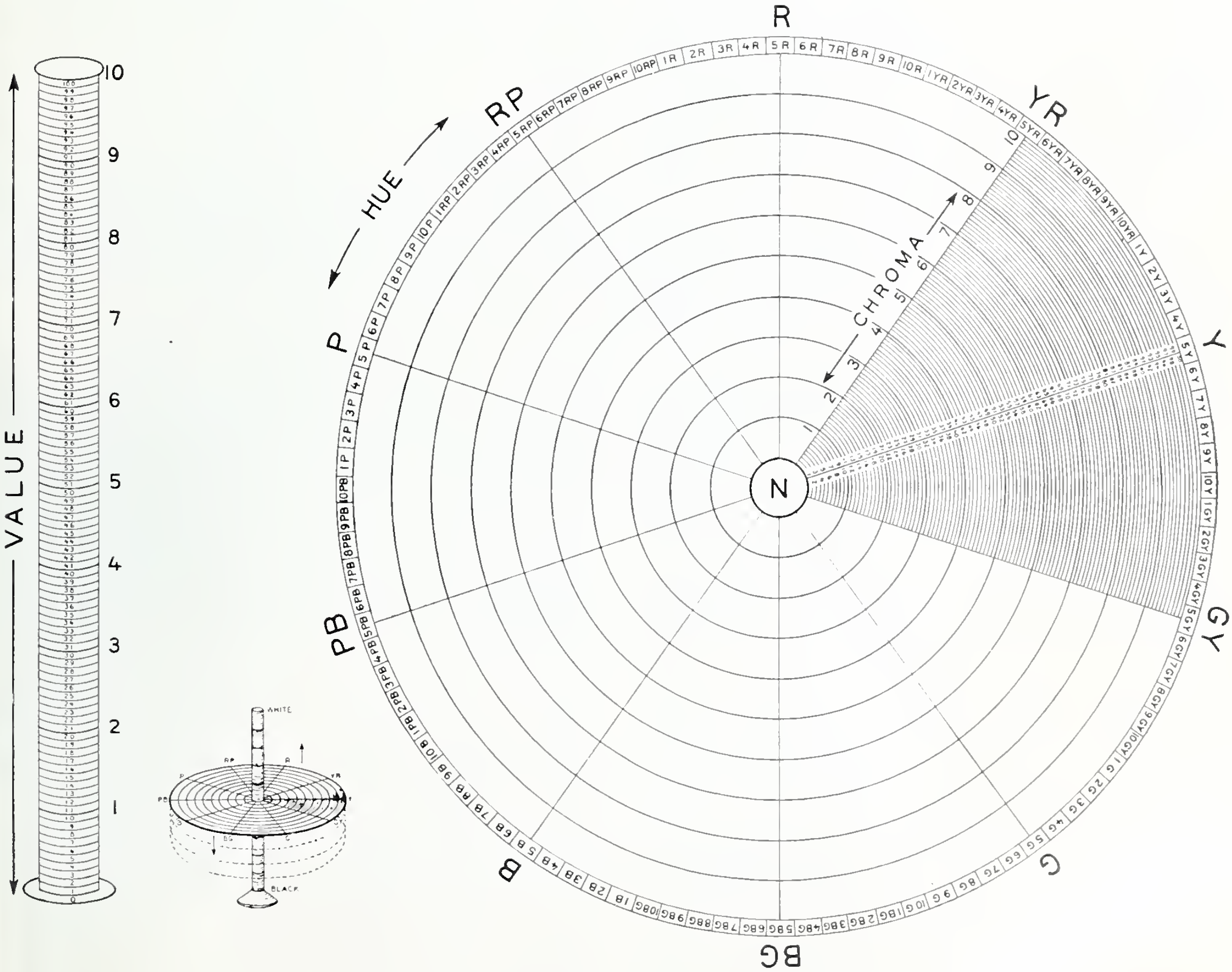

FIGURE 4.—Munsell color notation in terms of 10 and 100 steps in scales of hue, value, and chroma.

the 10 major hues is equally spaced visually (when held constant for value and chroma), and the circuit is divisible into 100 (or even 1,000) closer but still equally spaced hues in order to provide a numerical decimal notation as fine as may be needed for use in the most careful measurement problems. In teaching color in art classes the hue names and letters are generally used; when using the notation for measurement and specification purposes the letters are either supplanted altogether by numbers, or the hue notation is expressed by letter and number. A portion of the hue diagram is enlarged in figure 5 to show the relation of the letter, letter-and-number, and number notation for Munsell hue.

Munsell value is that attribute of all colors which permits them to be classed as equivalent to some member of a series of grays that are equally spaced under the standard conditions for which the scale was derived. The Munsell scale of grays extends from 0, black, to 10, white, and the use of decimal numbers (fig. 4) permits the value notation to be expressed as accurately as seems necessary for the purpose at hand.

Munsell chroma is that attribute of all colors possessing hue which determines their degree of difference from a gray of the same value. The notation is numerical, with 0 at gray, extending outward from the neutrals toward 10 or more for the strong colors. The chroma notation may be subdivided decimally (fig. 4); hence it allows a notation for as fine a degree of chroma difference as may be discriminated.

"The three attributes of color can be treated as quantities and specified numerically, if all discriminable colors are conceived to be arranged in a system such that neighboring members differ from each other in each of the three attributes by just noticeable degrees. Such a system is necessarily three-dimensional, and three ordinal values representing the positions of a given color in the several dimensions are needed to define the color."[12]

It is important in color work to understand thoroughly the three-dimensional concept of color that is illustrated on the small sketch in figure 4 and in figures 6 and 7.

[12] The 1921 Report of the Colorimetry Committee of the Optical Soc. Amer., Optical Soc. Amer. Jour. & Rev. Sci. Instr. 6: 527-596, illus. 1922. (See p. 536.)

The notation is written in the order *H V/C*. When no number precedes the hue letter the number 5 is assumed, as R 4/10 which may also be written 5R 4/10 or in the complete numerical system, 5-4/10. An intermediate color might be written as 7.5BG 4/2 or 7.5BG 4.2/2.4 if a finer discrimination is needed; in the complete numerical notation this would be written 57.5-4.2/2.4. When value or chroma is reported separately the position of the dividing line indicates which is meant, as 5/, which means 5 value, or /5, which means 5 chroma.

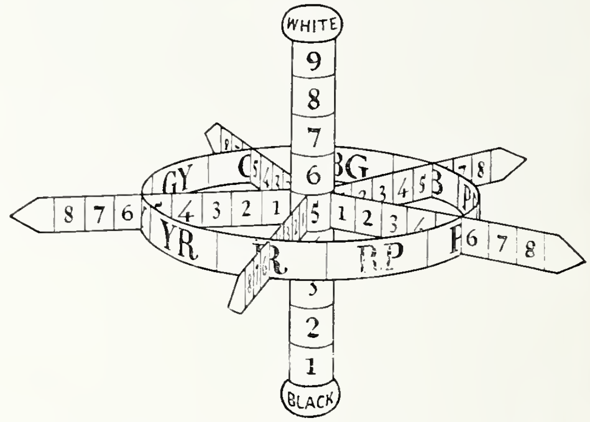

FIGURE 6.—Diagram to illustrate Munsell hue, value, and chroma in their relation to one another. The circular band represents the *hues* in proper sequence; the vertical center axis represents the scale of *value;* the paths outward from the center represent scales of *chroma,* increasing in strength in the direction indicated by the numbers. [Drawing by F. G. Cooper, from (*45*).]

Although there is no attempt in the Munsell system to equate the scales of hue, value, and chroma to each other, it is the purpose of the color charts to represent equal difference steps in the scales of each attribute. Color chips have been made and published on charts to represent the scales of hue, value, and chroma, first in the Atlas of the Munsell Color System (1915) and second in a revision in 1929 (*45*) which followed extensive research at the Munsell Research Laboratory and the National Bureau of Standards.

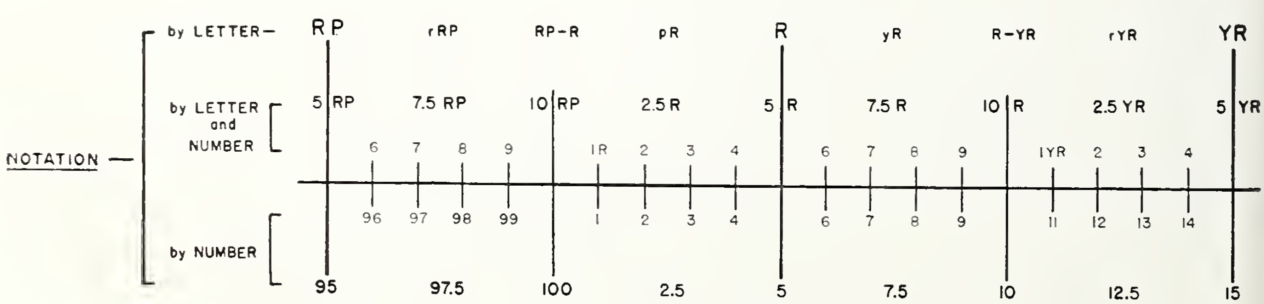

FIGURE 5.—Munsell hue notation showing relation of hue names, symbols, and numbers.

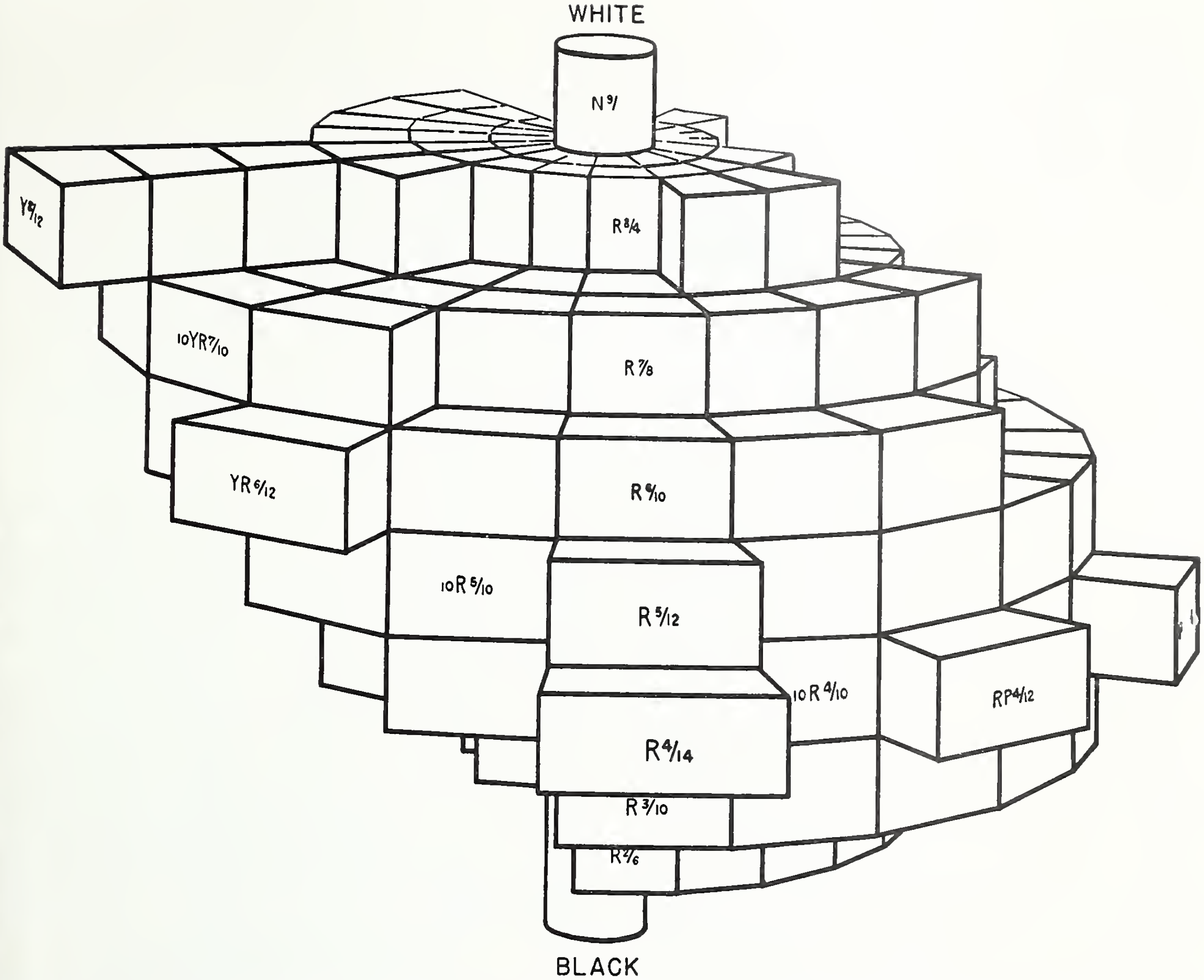

FIGURE 7.—One of the many ways in which the Munsell color solid can be illustrated. It may be drawn within a cylinder, or illustrated by a color tree; the vertical "constant-hue" charts, or the horizontal "constant-value" charts may be arranged in such a way as to get a skeleton outline of the solid; sometimes it is represented by a sphere, limited in diameter to the chroma of that hue which is weakest in value 5. (Drawing by M. E. Bond, from Bond-Nickerson report on Color Order Systems, Optical Soc. Amer. Jour. 32:714. 1942.)

Relation Between Methods

Since the I. C. I. colorimetric data were adopted in 1931 the practice has been to obtain dominant wave length and purity by use of the I. C. I. (x, y)-diagram. As already noted, large-scale diagrams for dominant wave length and purity as related to C illuminant were published in 1936 (*43*). The conversion from one method to the other is so easily made if one has large-scale charts before him, that often the difference between the concepts is not clearly kept in mind. A conversion diagram is easily made by plotting points representing the spectrum locus on an (x, y)-diagram and connecting these points to the illuminant point by straight lines. Halfway from spectrum to illuminant is a point representing 50 percent purity, and similar points may be designated for other percentages. The relation of the I. C. I. (x, y)-notation and the dominant wave length-purity notation is shown on such diagrams.

The relation between the Munsell notation and the I. C. I. and dominant wave length-purity notation is not so simple, but has now been clearly established.

Papers of 20 standard Munsell hues were spectrophotometrically measured at the Massachusetts Institute of Technology in 1934 and colorimetric data were published for illuminant C in 1940 (*21*). Meanwhile, similar measurements made at the National Bureau of Standards, resulted in publication of I. C. I. colorimetric data for four illuminants in 1943 (*39*). In the same year I. C. I. colorimetric results, based on spectrophotometric curves made in the laboratories of the Interchemical Corporation, were published for the remaining 20 Munsell hues and for the several hundred special colors made available since 1929 in Munsell notation (*23*). Thus I. C. I. data are now published for all but the newer repaints of the Munsell color chips, and data for most of these are available in the United States Department of Agriculture through the cooperation of

the color laboratory of the Philadelphia Navy Yard.[13]

While I. C. I. data were being obtained for the Munsell color chips, a study of the spacing of the Munsell system was made by a subcommittee of the Colorimetry Committee of the Optical Society of America. The first report (*46*) of this subcommittee, published in 1940, presents results of a systematic visual examination by 40 observers of the constant-value and constant-hue charts on three backgrounds—white, gray, and black. The second report (*47*) presents charts and tables constituting the definition of a psychophysical system based on the data of the first report but now smoothed on I. C. I. diagrams in relation to the colorimetric measurements provided for the Munsell chips (*21, 39, 23*). This smoothed Munsell system is now used as the basis for measurement work, the colors of the Munsell color chips being expressed—when accurate instead of approximate data are needed—in terms of the "re-notation" provided by the smoothed system (*47*) and the psychological color solid thereby defined (*61*). Thus the chip representing YR 6/12 on the Munsell chart may be 6YR 6.2/11.5, and Y 8/12 may be 5.5Y 7.9/12.3 in terms of the smoothed system. This will not matter when the Munsell charts are used for teaching visual color notations, but a knowledge of the tolerance within which these color chips meet the subcommittee specification becomes important in measurement and specification problems. It is much the same as measuring an inch by the use of a ruler for everyday work but by the use of micrometer calipers for accurate specification. An inch is the same in both cases, but in one it is measured to a closer tolerance than in the other.

The relations of Munsell hue, value, and chroma have thus been studied in I. C. I. terms and data are available for converting from one to the other. Table 1 gives I. C. I. (Y) equivalents for the recommended Munsell value scale. Figures 8 to 16 show the recommended loci for 40 constant hues and for constant chroma (even steps, 2, 4, etc.) in I. C. I. (x, y)-coordinates at values 1/ to 9/. These diagrams, or enlarged sections from them, are necessary for converting I. C. I. specifications to Munsell and vice versa.

In order to show the relation of Munsell hue to the I. C. I. (x, y)-diagram and some of the relations between the hue-value-chroma notation and the dominant wave length-purity notation, lines of constant hue are shown for 20 Munsell hues in figure 17. In this diagram the families of hue lines indicate the change in dominant wave length that is necessary to keep hue constant at various value and chroma levels. Chroma is not indicated in this figure because constant chroma for a given sample is indicated by a different (x, y)-point on the diagram for each change in value, as is clear by reference to figures 8 to 16. The closed lines indicate the theoretical limit beyond which one cannot have a nonfluorescent surface color for a given value level.

Although either the dominant wave length-purity notation or the hue-value-chroma notation may be applied directly in some grading work, it is the usual practice in color measurement to refer both of them to the I. C. I. (x, y)-diagram.[14] From the same I. C. I. data one may therefore obtain results in terms of either system.

For some problems it may not matter which system of notation is used. For example, a very good job of color standardization on rosin was done several years ago in the United States Department of Agriculture by B. A. Brice (*8*). The new standards that were adopted on May 6, 1936, superseded the 1923 Lovibond standards for rosin. Dr. Brice did a great deal of spectrophotometric work and developed an instrument that can be used for testing and selecting standards for rosin. The instrument reads transmittance in terms that can easily be transferred to (Y, x, y) terms. From these he obtained and reported the additional specifications of dominant wave length and purity.

Undoubtedly this method has been used in other cases for grading work, but the more usual method in the United States Department of Agriculture involves use of the Munsell system of color notation, since color measurements are thus kept in terms of scales whose steps closely approximate equal-sense intervals and give close correspondence to the visual judgments of inspectors or graders.

Since publication in 1943 of the several reports on the Munsell system (*39, 23, 47, 61*) it has been possible, regardless of the instrument used, to obtain Munsell notations[15] for illuminant C for any color for which I. C. I. data are known. It is possible to do this also by means of disk colorimetry, developed in the laboratories of the Department of Agriculture in order to provide a simple, rapid, and direct method for making color measurements.

DISK COLORIMETRY

Although the method of disk colorimetry as originally developed in the laboratories of the United States Department of Agriculture was tied up with the use of the Munsell system of notation, actually the method itself has nothing to do with Munsell. Disk colorimetry is a very simple and fundamentally sound method of additive colorimetry, suggested years ago by Clerk Maxwell by whose name we still call the type of disks cut with a radial slit so that several may be slipped together with

[13] First through J. J. Hanlon, later through H. A. Sloviter.

[14] It is to be hoped that some time in the future, after sufficient data are obtained, the I.C.I. system of colorimetry will be revised. This should not be done hastily, for it is better to get along with what we have than to keep revising year after year. But when the time does come data should become available for a standard observer both for light and for dark adaptation all through the spectrum with the three imaginary primaries selected so that an I.C.I. plot, based on a practical and widely used daylight illuminant, will indicate that equal distances on the diagram represent relatively equal sense differences. Such a hope could not have been entertained at the 1931 I.C.I. conference. But the adoption of the 1931 standards has enabled colorimetry to progress so much in the last decade that in another decade we may have data for an I.C.I. standard that will embody many more useful features than the present standard. Search for a uniform-chromaticity diagram, and for a method of relating I.C.I. data to various concepts of color solids more closely in agreement with the Munsell solid are moves in the right direction, and will eventually build up a body of information which can be used in revising the present I.C.I. method.

[15] Re-notation is the term used in the O.S.A.'s subcommittee report on spacing of the Munsell colors (*47*) to specify Munsell notations in accordance with the recommendations of the subcommittee.

TABLE 1.—I.C.I. (Y) equivalents (in percent relative to MgO) of the recommended Munsell value scale (V) from 0/ to 10/

V	Y_V (%)	V	Y_V (%)	V	Y_V (%)	V	Y_V (%)	V	Y_V (%)	V	Y_V (%)	V	Y_V (%)	V	Y_V (%)	V	Y_V (%)	V	Y_V (%)
10.00	102.56																		
9.99	102.30	8.99	78.45	7.99	58.92	6.99	42.92	5.99	29.94	4.99	19.68	3.99	11.935	2.99	6.511	1.99	3.100	0.99	1.196
8	102.04	8	78.23	8	58.74	8	42.77	8	29.82	8	19.59	8	11.870	8	6.468	8	3.075	8	1.182
7	101.78	7	78.02	7	58.57	7	42.63	7	29.71	7	19.50	7	11.805	7	6.425	7	3.050	7	1.168
6	101.52	6	77.80	6	58.39	6	42.49	6	29.59	6	19.41	6	11.740	6	6.382	6	3.025	6	1.154
5	101.25	5	77.59	5	58.22	5	42.34	5	29.48	5	19.32	5	11.675	5	6.339	5	3.000	5	1.141
9.94	100.99	8.94	77.38	7.94	58.04	6.94	42.20	5.94	29.36	4.94	19.23	3.94	11.611	2.94	6.296	1.94	2.975	0.94	1.128
3	100.73	3	77.16	3	57.87	3	42.06	3	29.25	3	19.14	3	11.547	3	6.254	3	2.950	3	1.114
2	100.47	2	76.95	2	57.69	2	41.92	2	29.13	2	19.06	2	11.483	2	6.212	2	2.925	2	1.101
1	100.21	1	76.74	1	57.52	1	41.77	1	29.02	1	18.97	1	11.419	1	6.170	1	2.901	1	1.087
0	99.95	0	76.53	0	57.35	0	41.63	0	28.90	0	18.88	0	11.356	0	6.128	0	2.877	0	1.074
9.89	99.69	8.89	76.32	7.89	57.17	6.89	41.49	5.89	28.79	4.89	18.79	3.89	11.292	2.89	6.086	1.89	2.853	0.89	1.060
8	99.44	8	76.11	8	57.00	8	41.35	8	28.68	8	18.70	8	11.229	8	6.045	8	2.829	8	1.047
7	99.18	7	75.90	7	56.83	7	41.21	7	28.57	7	18.62	7	11.167	7	6.003	7	2.805	7	1.034
6	98.92	6	75.69	6	56.66	6	41.07	6	28.45	6	18.53	6	11.104	6	5.962	6	2.781	6	1.021
5	98.66	5	75.48	5	56.48	5	40.93	5	28.34	5	18.44	5	11.042	5	5.921	5	2.758	5	1.008
9.84	98.41	8.84	75.27	7.84	56.31	6.84	40.79	5.84	28.23	4.84	18.36	3.84	10.980	2.84	5.881	1.84	2.735	0.84	0.995
3	98.15	3	75.06	3	56.14	3	40.65	3	28.12	3	18.27	3	10.918	3	5.841	3	2.712	3	.982
2	97.90	2	74.85	2	55.97	2	40.51	2	28.01	2	18.19	2	10.856	2	5.800	2	2.688	2	.969
1	97.64	1	74.64	1	55.80	1	40.37	1	27.90	1	18.10	1	10.795	1	5.760	1	2.665	1	.956
0	97.39	0	74.44	0	55.63	0	40.23	0	27.78	0	18.02	0	10.734	0	5.720	0	2.642	0	.943
9.79	97.14	8.79	74.23	7.79	55.46	6.79	40.09	5.79	27.67	4.79	17.93	3.79	10.673	2.79	5.680	1.79	2.620	0.79	.931
8	96.88	8	74.02	8	55.29	8	39.95	8	27.56	8	17.85	8	10.612	8	5.641	8	2.598	8	.918
7	96.63	7	73.82	7	55.12	7	39.82	7	27.45	7	17.76	7	10.551	7	5.602	7	2.575	7	.906
6	96.38	6	73.61	6	54.95	6	39.68	6	27.34	6	17.68	6	10.491	6	5.563	6	2.553	6	.893
5	96.13	5	73.40	5	54.78	5	39.54	5	27.23	5	17.60	5	10.431	5	5.524	5	2.531	5	.881
9.74	95.88	8.74	73.20	7.74	54.62	6.74	39.40	5.74	27.12	4.74	17.51	3.74	10.371	2.74	5.485	1.74	2.509	0.74	.868
3	95.63	3	72.99	3	54.45	3	39.27	3	27.02	3	17.43	3	10.311	3	5.447	3	2.487	3	.856
2	95.38	2	72.79	2	54.28	2	39.13	2	26.91	2	17.34	2	10.252	2	5.408	2	2.465	2	.844
1	95.13	1	72.59	1	54.11	1	39.00	1	26.80	1	17.26	1	10.193	1	5.370	1	2.443	1	.832
0	94.88	0	72.38	0	53.94	0	38.86	0	26.69	0	17.18	0	10.134	0	5.332	0	2.422	0	.819
9.69	94.63	8.69	72.18	7.69	53.78	6.69	38.72	5.69	26.58	4.69	17.10	3.69	10.075	2.69	5.295	1.69	2.401	0.69	.807
8	94.38	8	71.98	8	53.61	8	38.59	8	26.48	8	17.02	8	10.017	8	5.257	8	2.380	8	.795
7	94.14	7	71.78	7	53.45	7	38.45	7	26.37	7	16.93	7	9.959	7	5.220	7	2.359	7	.783
6	93.89	6	71.57	6	53.28	6	38.32	6	26.26	6	16.85	6	9.901	6	5.183	6	2.338	6	.771
5	93.64	5	71.37	5	53.12	5	38.18	5	26.15	5	16.77	5	9.843	5	5.146	5	2.317	5	.759
9.64	93.40	8.64	71.17	7.64	52.95	6.64	38.05	5.64	26.05	4.64	16.69	3.64	9.785	2.64	5.109	1.64	2.296	0.64	.747
3	93.15	3	70.97	3	52.79	3	37.92	3	25.94	3	16.61	3	9.728	3	5.072	3	2.276	3	.735
2	92.91	2	70.77	2	52.62	2	37.78	2	25.84	2	16.53	2	9.671	2	5.036	2	2.256	2	.723
1	92.66	1	70.57	1	52.46	1	37.65	1	25.73	1	16.45	1	9.614	1	5.000	1	2.236	1	.711
0	92.42	0	70.37	0	52.30	0	37.52	0	25.62	0	16.37	0	9.557	0	4.964	0	2.216	0	.699
9.59	92.18	8.59	70.17	7.59	52.13	6.59	37.38	5.59	25.52	4.59	16.29	3.59	9.501	2.59	4.928	1.59	2.196	0.59	.687
8	91.93	8	69.97	8	51.97	8	37.25	8	25.41	8	16.21	8	9.445	8	4.892	8	2.176	8	.675
7	91.69	7	69.78	7	51.81	7	37.12	7	25.31	7	16.13	7	9.389	7	4.857	7	2.156	7	.663
6	91.45	6	69.58	6	51.64	6	36.99	6	25.20	6	16.05	6	9.333	6	4.822	6	2.136	6	.651
5	91.21	5	69.38	5	51.48	5	36.86	5	25.10	5	15.97	5	9.277	5	4.787	5	2.116	5	.640
9.54	90.97	8.54	69.18	7.54	51.32	6.54	36.72	5.54	25.00	4.54	15.89	3.54	9.222	2.54	4.752	1.54	2.097	0.54	.628
3	90.73	3	68.99	3	51.16	3	36.59	3	24.89	3	15.81	3	9.167	3	4.717	3	2.078	3	.617
2	90.49	2	68.79	2	51.00	2	36.46	2	24.79	2	15.74	2	9.112	2	4.682	2	2.059	2	.605
1	90.25	1	68.59	1	50.84	1	36.33	1	24.69	1	15.66	1	9.058	1	4.648	1	2.040	1	.593
0	90.01	0	68.40	0	50.68	0	36.20	0	24.58	0	15.57	0	9.003	0	4.614	0	2.021	0	.581
9.49	89.77	8.49	68.20	7.49	50.52	6.49	36.07	5.49	24.48	4.49	15.49	3.49	8.949	2.49	4.580	1.49	2.002	0.49	.570
8	89.53	8	68.01	8	50.36	8	35.94	8	24.38	8	15.42	8	8.895	8	4.546	8	1.983	8	.559
7	89.30	7	67.81	7	50.20	7	35.81	7	24.28	7	15.34	7	8.841	7	4.512	7	1.965	7	.547
6	89.06	6	67.62	6	50.04	6	35.68	6	24.17	6	15.26	6	8.787	6	4.479	6	1.947	6	.535
5	88.82	5	67.43	5	49.88	5	35.56	5	24.07	5	15.18	5	8.734	5	4.446	5	1.929	5	.524
9.44	88.59	8.44	67.23	7.44	49.72	6.44	35.43	5.44	23.97	4.44	15.11	3.44	8.681	2.44	4.413	1.44	1.910	0.44	.513
3	88.35	3	67.04	3	49.56	3	35.30	3	23.87	3	15.03	3	8.628	3	4.380	3	1.892	3	.501
2	88.12	2	66.85	2	49.41	2	35.17	2	23.77	2	14.96	2	8.575	2	4.347	2	1.874	2	.489
1	87.88	1	66.66	1	49.25	1	35.04	1	23.67	1	14.88	1	8.523	1	4.314	1	1.856	1	.478
0	87.65	0	66.46	0	49.09	0	34.92	0	23.57	0	14.81	0	8.471	0	4.282	0	1.838	0	.467
9.39	87.41	8.39	66.27	7.39	48.93	6.39	34.79	5.39	23.47	4.39	14.73	3.39	8.419	2.39	4.250	1.39	1.821	0.39	.455
8	87.18	8	66.08	8	48.78	8	34.66	8	23.37	8	14.66	8	8.367	8	4.218	8	1.803	8	.444
7	86.95	7	65.89	7	48.62	7	34.54	7	23.27	7	14.58	7	8.316	7	4.186	7	1.786	7	.432
6	86.72	6	65.70	6	48.47	6	34.41	6	23.17	6	14.51	6	8.264	6	4.154	6	1.769	6	.421
5	86.48	5	65.51	5	48.31	5	34.28	5	23.07	5	14.43	5	8.213	5	4.123	5	1.752	5	.409
9.34	86.25	8.34	65.32	7.34	48.16	6.34	34.16	5.34	22.97	4.34	14.36	3.34	8.162	2.34	4.092	1.34	1.735	0.34	.398
3	86.02	3	65.13	3	48.00	3	34.03	3	22.87	3	14.28	3	8.111	3	4.060	3	1.718	3	.386
2	85.79	2	64.94	2	47.85	2	33.91	2	22.78	2	14.21	2	8.060	2	4.029	2	1.701	2	.375
1	85.56	1	64.76	1	47.69	1	33.78	1	22.68	1	14.14	1	8.010	1	3.998	1	1.684	1	.363
0	85.33	0	64.57	0	47.54	0	33.66	0	22.58	0	14.07	0	7.960	0	3.968	0	1.667	0	.352
9.29	85.10	8.29	64.38	7.29	47.38	6.29	33.54	5.29	22.48	4.29	13.99	3.29	7.910	2.29	3.938	1.29	1.650	0.29	.341
8	84.88	8	64.19	8	47.23	8	33.41	8	22.38	8	13.92	8	7.860	8	3.907	8	1.634	8	.329
7	84.65	7	64.01	7	47.08	7	33.29	7	22.29	7	13.85	7	7.811	7	3.877	7	1.618	7	.318
6	84.42	6	63.82	6	46.92	6	33.16	6	22.19	6	13.78	6	7.762	6	3.847	6	1.601	6	.306
5	84.19	5	63.63	5	46.77	5	33.04	5	22.09	5	13.70	5	7.713	5	3.817	5	1.585	5	.295
9.24	83.97	8.24	63.45	7.24	46.62	6.24	32.92	5.24	22.00	4.24	13.63	3.24	7.664	2.24	3.787	1.24	1.569	0.24	.283
3	83.74	3	63.26	3	46.47	3	32.80	3	21.90	3	13.56	3	7.615	3	3.758	3	1.553	3	.272
2	83.52	2	63.08	2	46.32	2	32.67	2	21.81	2	13.49	2	7.567	2	3.729	2	1.537	2	.260
1	83.29	1	62.89	1	46.17	1	32.55	1	21.71	1	13.42	1	7.519	1	3.700	1	1.521	1	.248
0	83.07	0	62.71	0	46.02	0	32.43	0	21.62	0	13.35	0	7.471	0	3.671	0	1.506	0	.237
9.19	82.84	8.19	62.52	7.19	45.87	6.19	32.31	5.19	21.52	4.19	13.28	3.19	7.423	2.19	3.642	1.19	1.490	0.19	.225
8	82.62	8	62.34	8	45.72	8	32.19	8	21.43	8	13.21	8	7.375	8	3.613	8	1.475	8	.214
7	82.39	7	62.16	7	45.57	7	32.07	7	21.33	7	13.14	7	7.328	7	3.585	7	1.459	7	.202
6	82.17	6	61.98	6	45.42	6	31.95	6	21.24	6	13.07	6	7.281	6	3.557	6	1.444	6	.191
5	81.95	5	61.79	5	45.27	5	31.83	5	21.14	5	13.00	5	7.234	5	3.529	5	1.429	5	.179
9.14	81.73	8.14	61.61	7.14	45.12	6.14	31.71	5.14	21.05	4.14	12.93	3.14	7.187	2.14	3.501	1.14	1.413	0.14	.167
3	81.50	3	61.43	3	44.97	3	31.59	3	20.96	3	12.86	3	7.140	3	3.473	3	1.398	3	.155
2	81.28	2	61.25	2	44.82	2	31.47	2	20.86	2	12.80	2	7.094	2	3.445	2	1.383	2	.143
1	81.06	1	61.07	1	44.67	1	31.35	1	20.77	1	12.73	1	7.048	1	3.418	1	1.368	1	.131
0	80.84	0	60.88	0	44.52	0	31.23	0	20.68	0	12.66	0	7.002	0	3.391	0	1.354	0	.120
9.09	80.62	8.09	60.70	7.09	44.38	6.09	31.11	5.09	20.59	4.09	12.59	3.09	6.956	2.09	3.364	1.09	1.339	0.09	.108
8	80.40	8	60.52	8	44.23	8	30.99	8	20.49	8	12.52	8	6.911	8	3.337	8	1.324	8	.096
7	80.18	7	60.35	7	44.08	7	30.87	7	20.40	7	12.46	7	6.866	7	3.310	7	1.310	7	.084
6	79.97	6	60.17	6	43.94	6	30.75	6	20.31	6	12.39	6	6.821	6	3.283	6	1.295	6	.073
5	79.75	5	59.99	5	43.79	5	30.64	5	20.22	5	12.32	5	6.776	5	3.256	5	1.281	5	.061
9.04	79.53	8.04	59.81	7.04	43.64	6.04	30.52	5.04	20.13	4.04	12.26	3.04	6.731	2.04	3.230	1.04	1.267	0.04	.049
3	79.31	3	59.63	3	43.50	3	30.40	3	20.04	3	12.19	3	6.687	3	3.204	3	1.253	3	.036
2	79.10	2	59.45	2	43.35	2	30.28	2	19.95	2	12.12	2	6.643	2	3.178	2	1.238	2	.024
1	78.88	1	59.28	1	43.21	1	30.17	1	19.86	1	12.06	1	6.599	1	3.152	1	1.224	1	.012
0	78.66	0	59.10	0	43.06	0	30.05	0	19.77	0	12.00	0	6.555	0	3.126	0	1.210	0	.000

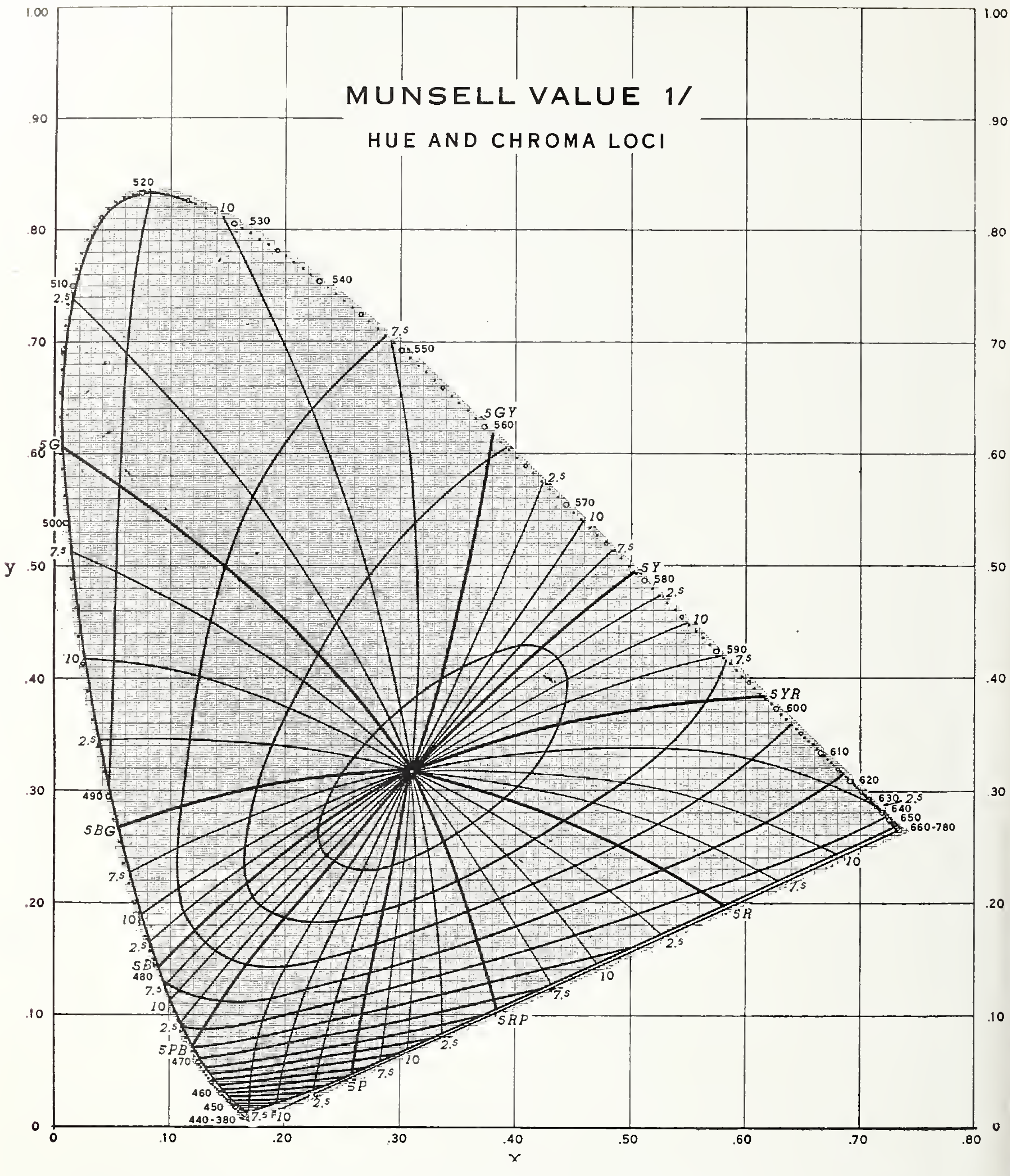

FIGURE 8.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 1/ for I.C.I. illuminant C.

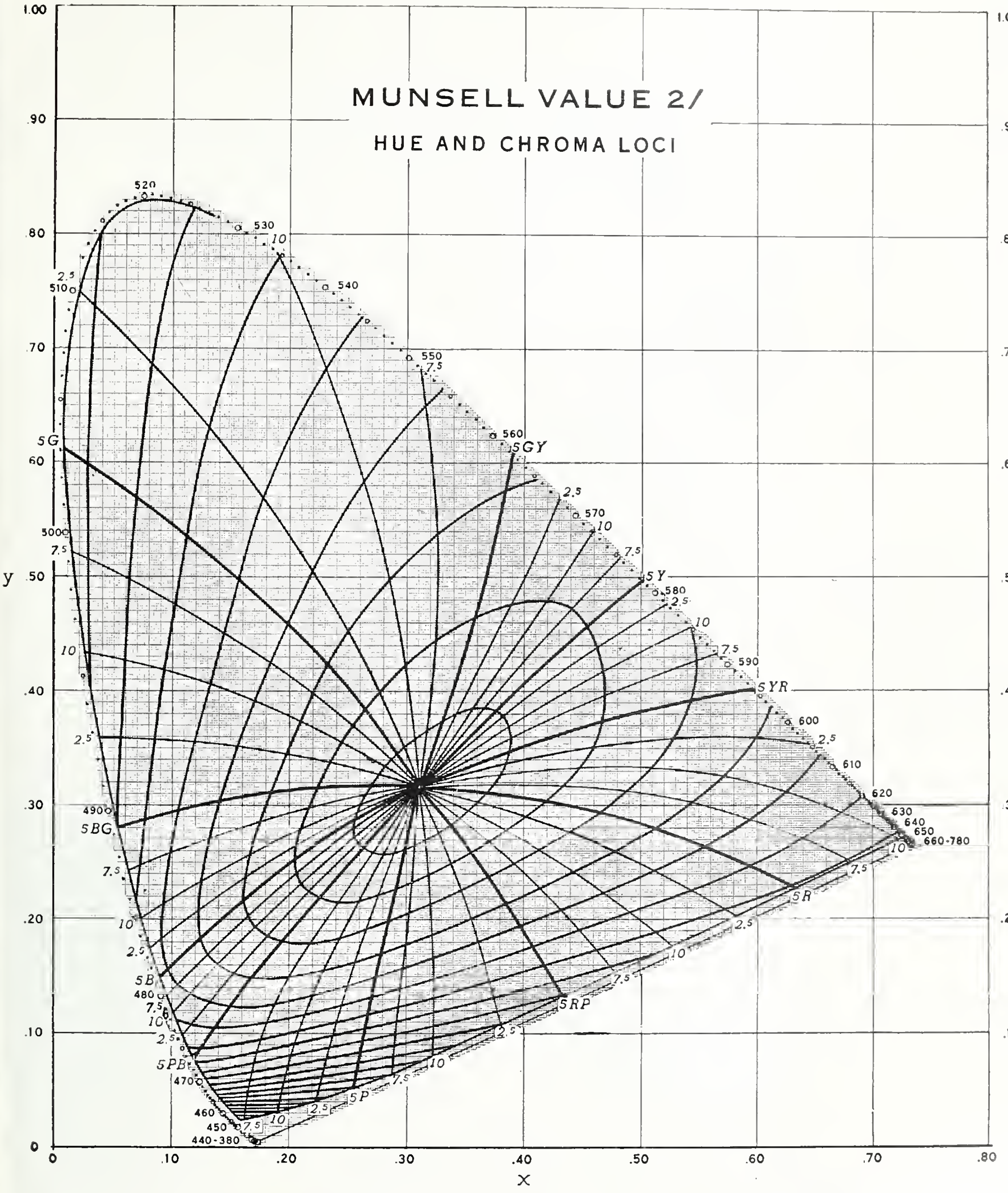

FIGURE 9.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 2/ for I.C.I. illuminant C.

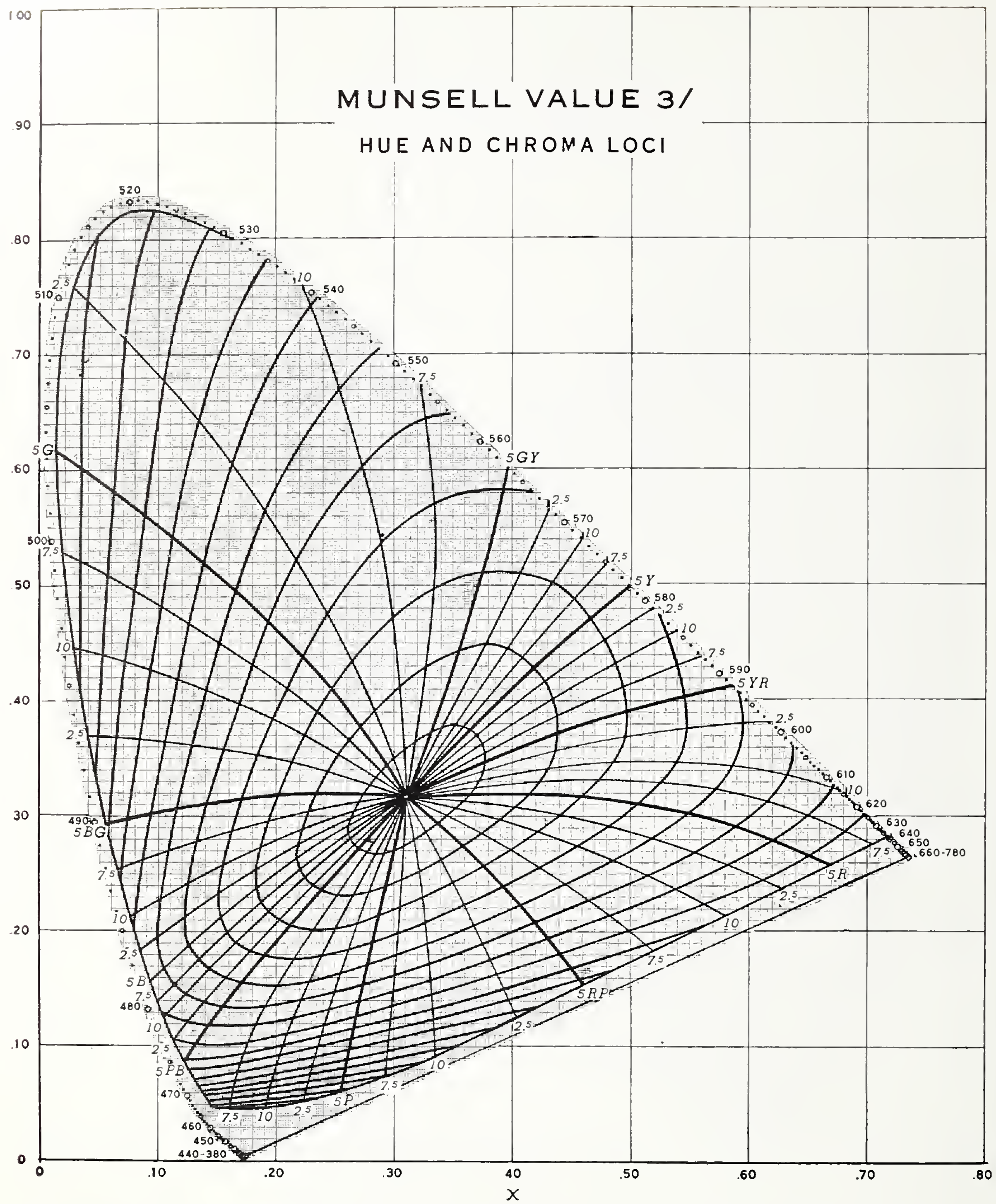

FIGURE 10.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 3/ for I.C.I. illuminant C.

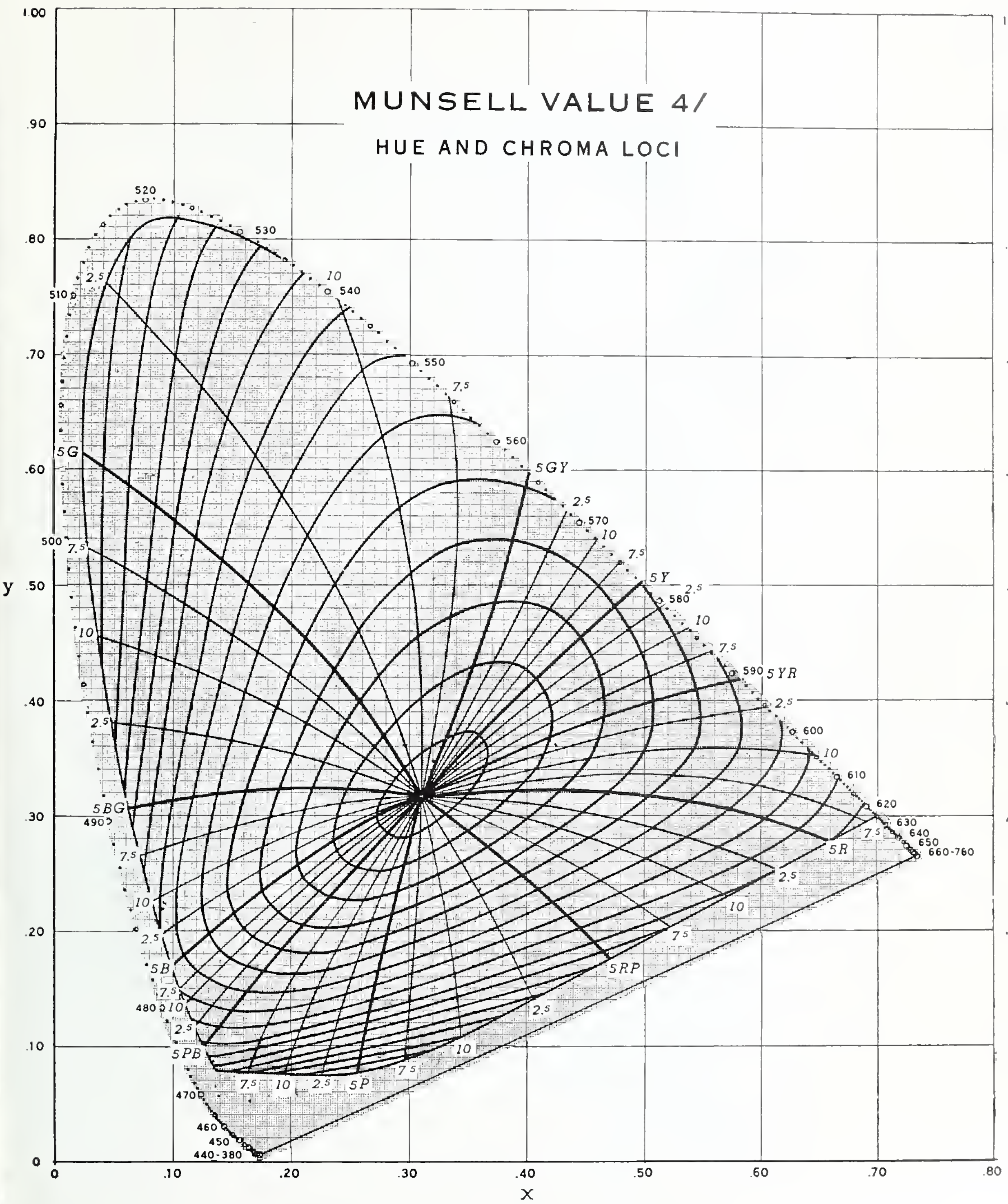

FIGURE 11.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 4/ for I.C.I. illuminant C.

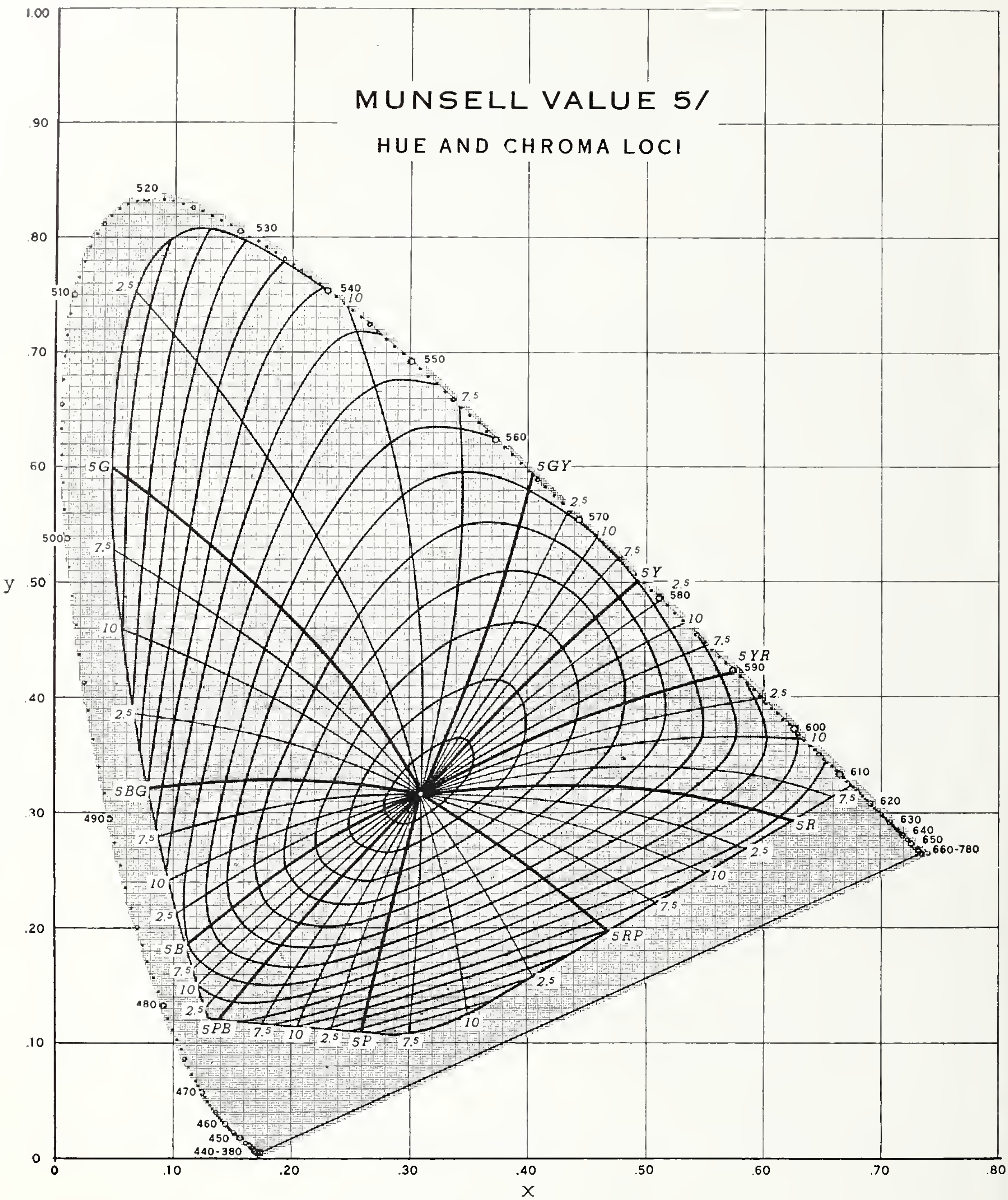

FIGURE 12.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 5/ for I.C.I. illuminant C.

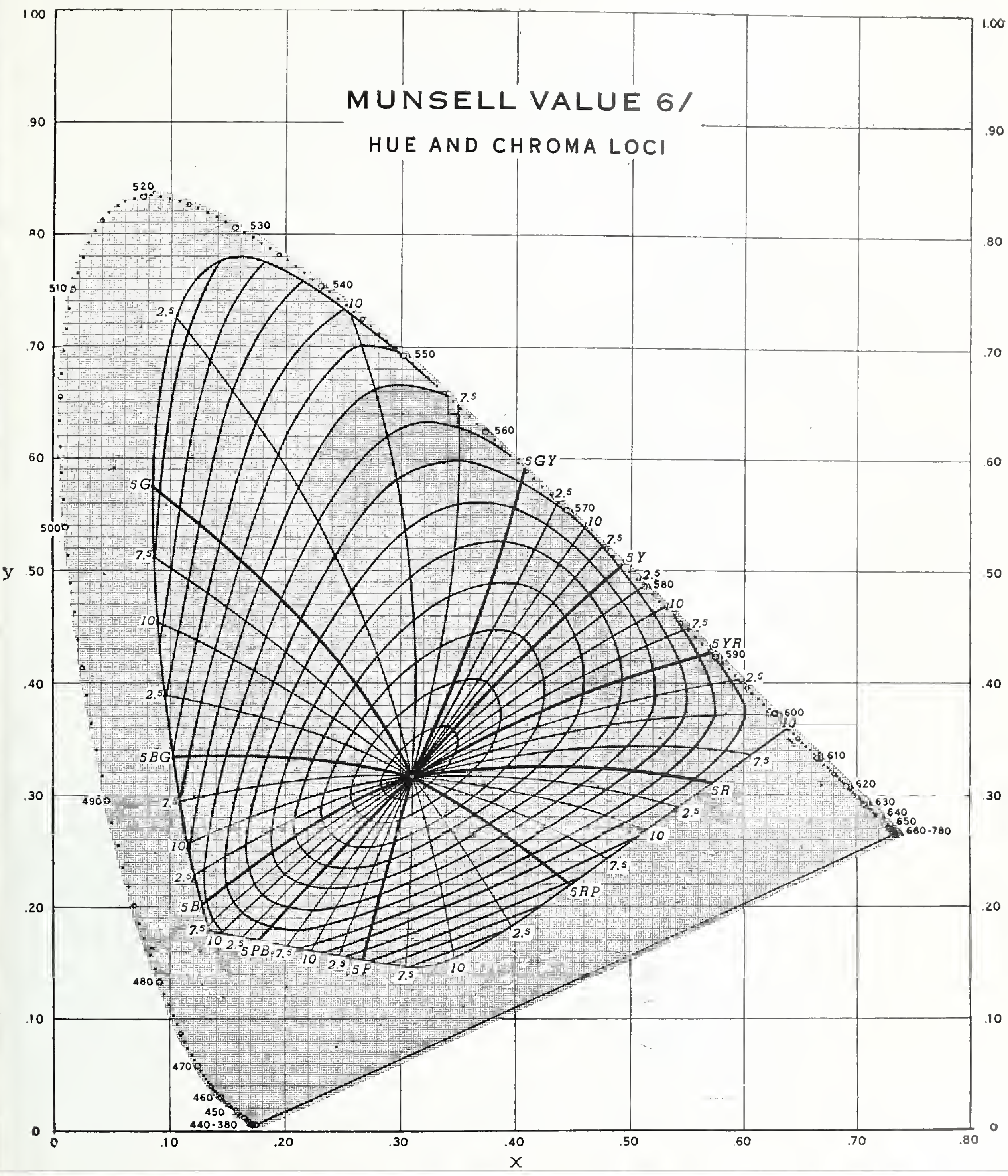

FIGURE 13.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 6/ for I.C.I. illuminant C.

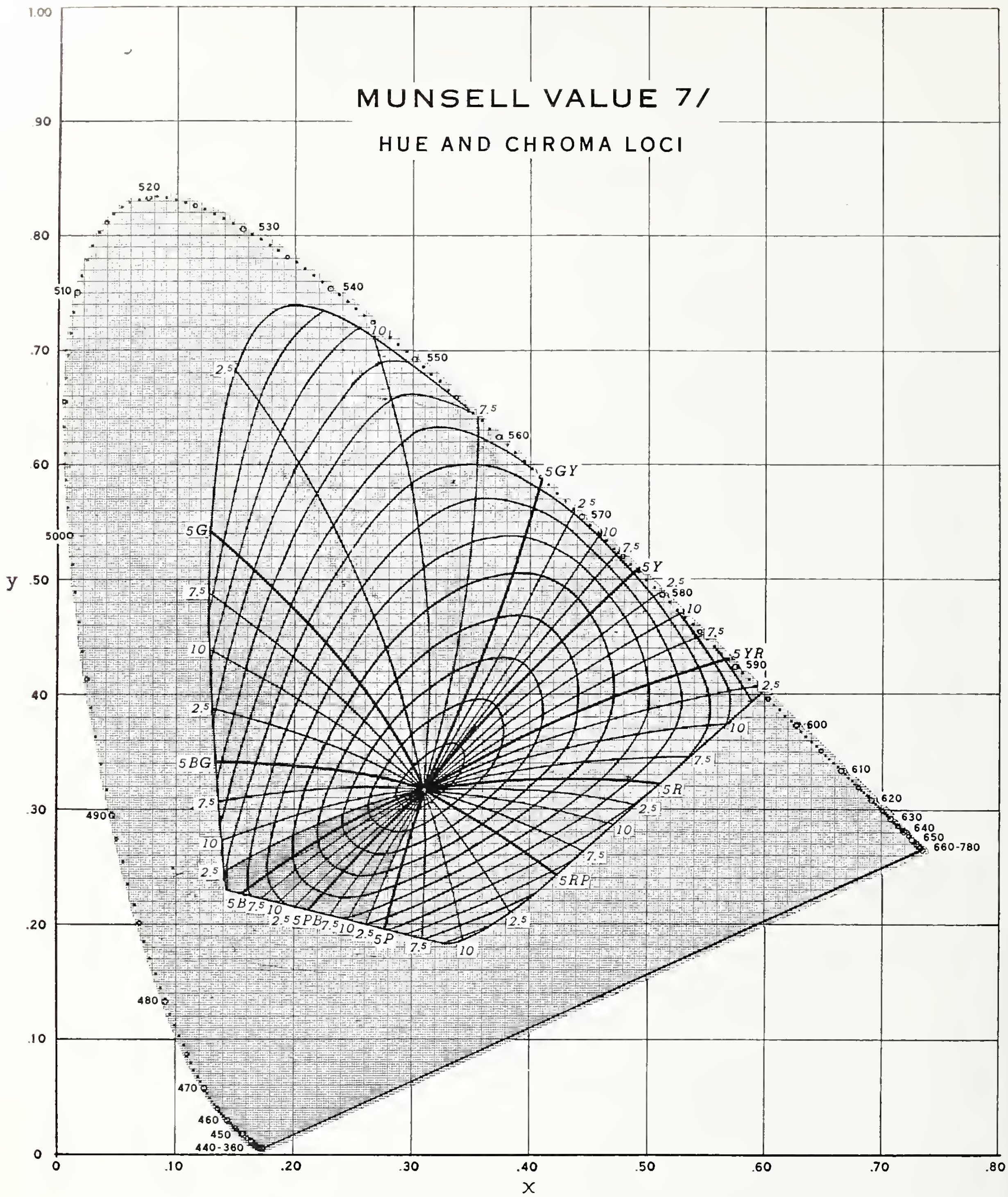

FIGURE 14.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 7/ for I.C.I. illuminant C.

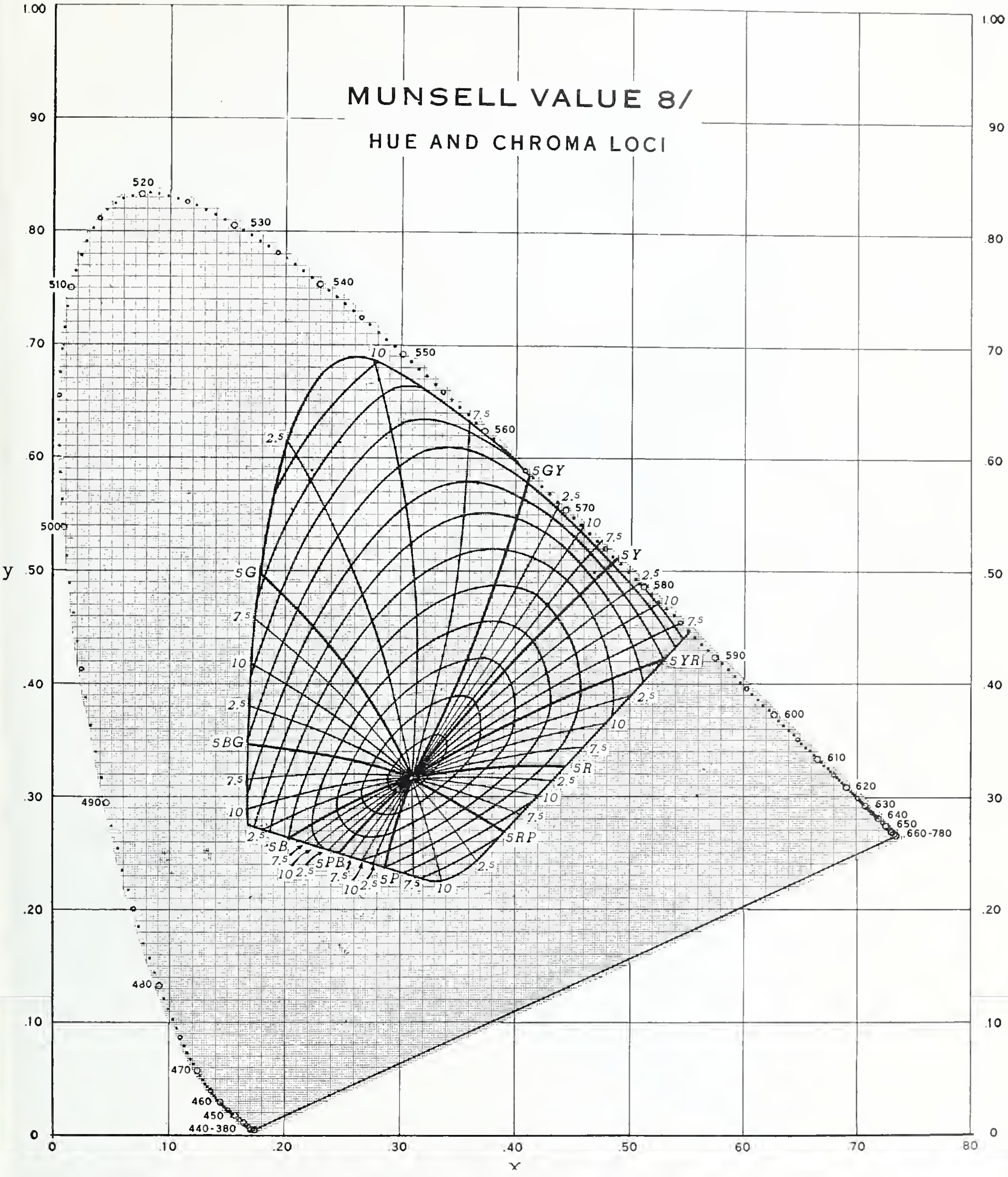

FIGURE 15.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 8/ for I.C.I. illuminant C.

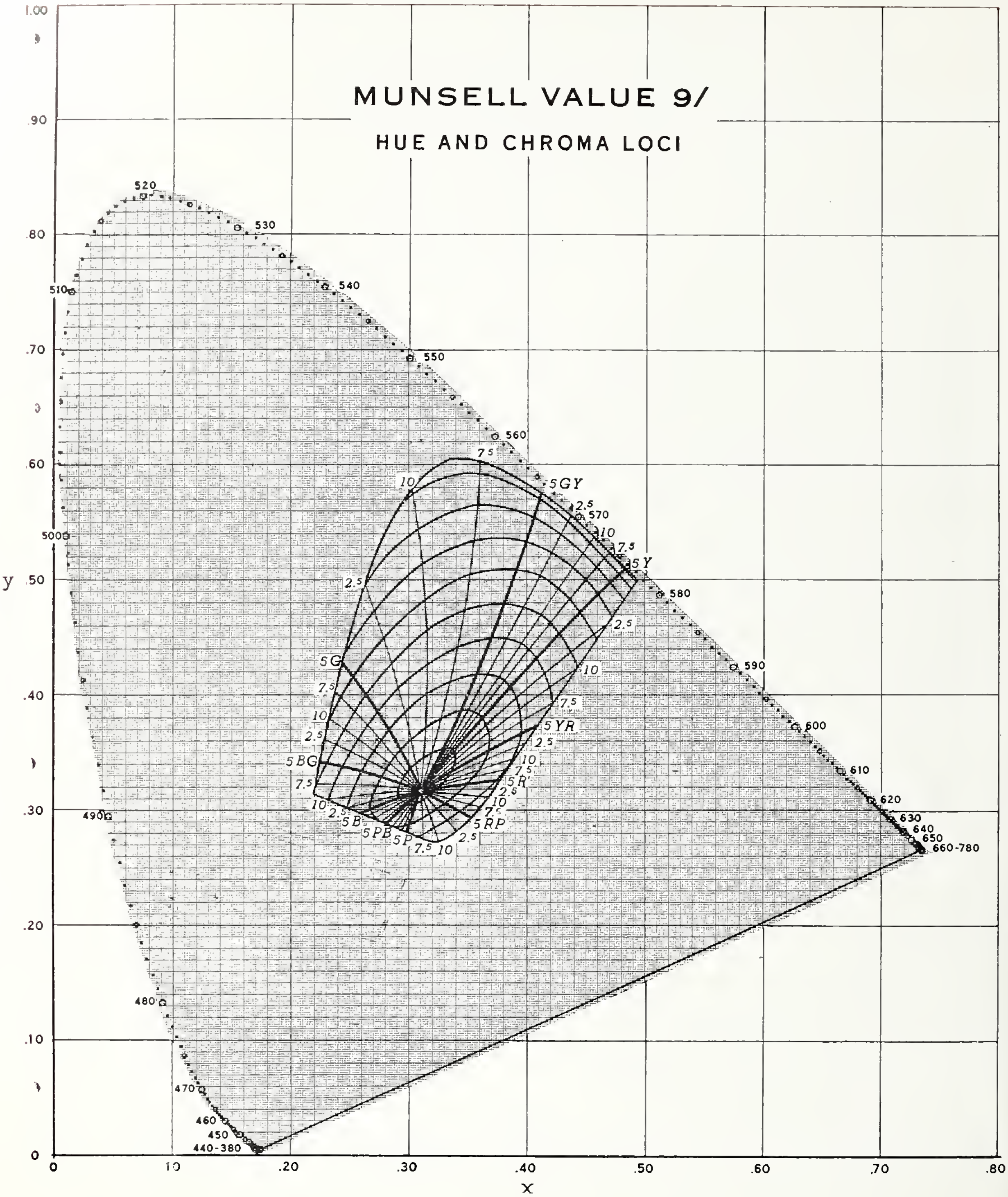

FIGURE 16.—Loci of constant-hue and constant-chroma in I.C.I. (x, y)-coordinates at value 9/ for I.C.I. illuminant C.

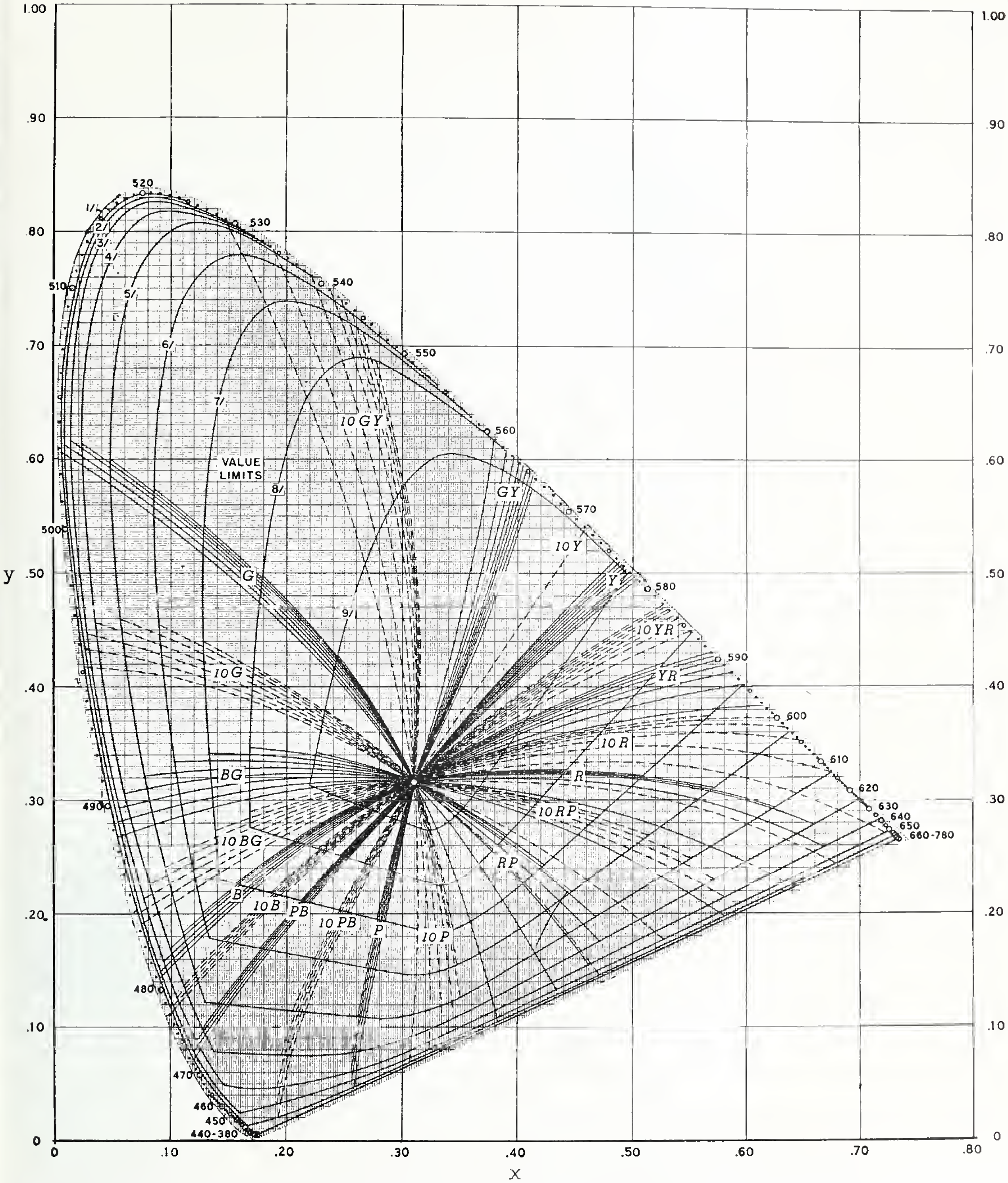

FIGURE 17.—Master hue chart in I.C.I. (x, y)-coordinates showing the recommended loci of constant hue for 20 standard Munsell hues at value levels 1/ through 9/. The families of hue lines indicate the change in dominant wave length that is necessary to keep hue constant at various value and chroma levels. The closed lines indicate the theoretical (MacAdam) limit beyond which nonfluorescent surface colors are not possible for the different value levels 1/ to 9/. The center closed line represents the limit colors available at value 9/; the limit colors at 1/ extend almost to the spectrum locus. The hue lines extend only to the theoretical limit for the value they represent.

portions of each visible. (See fig. 18.) By the use of Maxwell disks and a motor on which to spin them at a speed great enough so that there is no flicker, any color that lies in the color solid within the volumes intermediate to the colors of the disks used, may be matched. Precision in matching can be self-taught; an observer has either to make many measurements and use an average, or reduce his scatter to a minimum and use fewer measurements. He can decide for himself when he is able regularly to repeat his readings to a tolerance that is satisfactory for the studies he wishes to make.

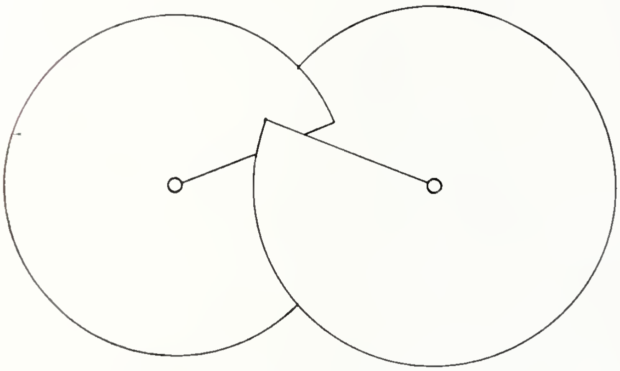

FIGURE 18.—Maxwell disks, cut with radial slit so that several may be slipped together with portions of each visible, for use in spinning colors together.

Early Method

In 1929, when the method was first published (*48*), there were no internationally standardized methods such as the I. C. I. to make possible accurate calculations of added colorimetric functions. Instead, Munsell disks were spun together and the resultant color expressed in approximate Munsell terms by calculations involving the use of percentages of the disks used, and the Munsell notation for the hue, value, and chroma of each disk. This method is still used when conversion tables are already worked out on this basis for single commodities.

These formulas, as developed and published for use with early Munsell standard papers (issued before 1929), are as follows:

Symbols:	A = Area, in percent	B = Brilliance (lightness) (value)
	H = Hue	C = Chroma (saturation)
		R = Reflectance (I.C.I. Y)
		x = 1st hue, clockwise
Notation:	H^B/c	z = 2d hue, clockwise
		P = Power (BxC)

Formulas:

$$\text{Hue: } z - \frac{\Sigma(A_xP_x)}{\Sigma(A_xP_x) + \Sigma(A_zP_z)}(z - x)$$

$$\text{Brilliance: } \sqrt{\frac{A_1B_1^2 + A_2B_2^2 + \cdots\cdots}{100}}$$

$$\text{Chroma: } \frac{A_1C_1 + A_2C_2 + \cdots\cdots}{100}$$

A new publication of Munsell standard cards was made in 1929, and thereafter the following substitution was made in the brilliance formula:

$$R = \frac{A_1R_1 + A_2R_2 + \cdots\cdots}{100}$$

• R (reflectance) was then converted to B (brilliance) from the following:

Reflectance	Brilliance	Reflectance	Brilliance
2.90	2	27.30	6
5.95	3	38.90	7
11.05	4	53.60	8
18.00	5	72.80	9
		100.00	10

Since these formulas were approximate only, certain precautions were cited when using them: (1) The Munsell hues selected should not be more than one-tenth of the hue circle apart; (2) disks of dark Munsell value, 1/ and 2/, should not be used when it is possible to use lighter colors; and (3) a single set of four disks should be used throughout any one piece of work whenever practicable.

Present Method

Use of standard I. C. I. tristimulus (X, Y, Z)-data in disk colorimetry now makes it possible to use accurate instead of approximate formulas.[16] Although it is usual to use Munsell disks [they are easily obtainable in disk form and are already measured in I. C. I. terms (*39, 23*)], any other disks for which I. C. I. data are available can be used. Disk colorimetry follows the laws of additive color mixture; therefore one has only to know the I. C. I. (X, Y, Z)-data for the series of disks used and the areas of each exposed in making a color match in order to compute the (X, Y, Z)-data for the color match of a given sample, the computation being made by the center of gravity principle. The choice of disks for matching a particular color or series of colors is greatly simplified by an understanding of the three-dimensional relationship of the psychological attributes of color as typified by the Munsell solid illustrated in figures 6 and 7. Any color may be matched by a proper choice of four disks, if the color to be matched lies in the geometric space intermediate to the four that are chosen. These should include two neutrals, one lighter and one darker than the sample, and strong chromas of two hues that lie on either side of the hue to be matched.

Suppose, for example, that a cotton sample is to be matched and that the disks used are a yellow-red, a yellow, a white, and a light gray for which I. C. I. (X, Y, Z)-data are known for illuminant C as follows:

Yellow-red disk:	$X = 0.3962$	$Y = 0.3241$	$Z = 0.0617$
Yellow disk:	$X = .5374$	$Y = .5706$	$Z = .0697$
White disk:	$X = .8119$	$Y = .8311$	$Z = .9455$
Light gray disk:	$X = .4337$	$Y = .4433$	$Z = .5285$

Suppose further that it took 10 percent of the yellow-red, 10 percent of the yellow, 20 percent of the white, and 60 percent of the gray to match the cotton. The tristimulus values (X, Y, Z) for this color are obtained as a weighted mean of the (X, Y, Z)-data for each disk

[16] NICKERSON, D. USE OF I.C.I. TRISTIMULUS VALUES IN DISK COLORIMETRY. U. S. Dept. Agr. 17 pp., illus. 1938. [Processed.]

used, the weights being proportional to disk area. This results in $X = 0.5159$, $Y = 0.5217$, $Z = 0.5194$, with fractional (x, y, z)-data of $x = 0.3313$, $y = 0.3351$, and $z = 0.3336$. Conversion either to the dominant wave length-purity notation, or the Munsell notation may be made by use of the (Y and x, y)-data, the first by reference to the Handbook of Colorimetry (*43*) and the second by reference to table 1 and figures 8 to 16 of this publication.[17]

Disk colorimetry provides a direct and useful method of colorimetry that can be expressed in any color notation, provided accurate I. C. I. conversion data are available for the notation to be used. The above data have the following equivalents:

I.C.I. notation: $X = 0.5159$, $Y = 0.5217$, $Z = 0.5194$; $x = 0.3313$, $y = 0.3351$

Dominant wave length-purity notation:[18]
Dom $\lambda = 579$, $P_e = 11$ percent

Munsell notation:[19]
Hue = 10YR, value = 7.6/, chroma = /1.4

Maerz and Paul:[20] Somewhere between 11-1-A and 12-2-A

Ostwald:[21] About halfway between 2-ec and neutral C

Instruments

The simplest instrumental set-up for disk colorimetry is a motor adjusted for spinning disks on a central spindle (fig. 19) and color disks that may be spun in juxtaposition to the sample, with the areas of the disks adjusted until the color of the spinning disks matches the color of the sample. The addition of a neutral mask to provide equal areas of disk and sample (fig. 19) and of standard conditions of illumination and viewing will change this fairly crude method to one that can be used for careful work. If color judgments are to be made with the eye,[22] then the color normality of the eyes should be known, and all possible external conditions used in judging the match should be standardized so that measurements may be repeated. That is why early in this work, with a rather large amount of color measurement to be undertaken, instruments were designed to standardize as many conditions as possible.

The most simple set-up used in this type of work is illustrated in figure 19 where the cotton sample gives a reasonably homogeneous color surface to match. In early work samples, like hay, that were not so homogeneous in color, were spun to give a color that could be matched with disks.

The next addition was the use of artificial daylight illumination—standardized as to quality, amount, and direction—so that readings on different days could be made under the same conditions of illumination.

Next came the addition of an optical eyepiece designed so that equal areas from the disks and sample could be brought into juxtaposition in a divided field. This eyepiece, used in connection with standard illumination, is still employed in many laboratories for the disk measurement of liquids, semiliquids, and granular products.

Finally there came instruments designed to supplant the actual spinning of the disks by a moving optical part, and to include sample and disk illumination as a part of the instrument. Such instruments, known as disk colorimeters, were first made[23] for the United States Department of Agriculture in types shown in figures 20 and 21 (*49*) to match samples ranging in size from 1 to 14 inches in diameter (for a large slug of hay), and the more recently developed[24] compact and useful instruments of the type shown in figure 22. Although the first type of instrument is no longer made commercially, several are in regular use. A newly developed model of the second type is expected to be put into postwar production. It has several very useful features in addition to those shown in figure 22. In the first instruments, daylight filters were used that gave an effective color temperature of about 4,500° K; the later type gave about 6,500° K (*51*).

Descriptions of the development of this work are given in following paragraphs so that persons who have occasional color problems to solve need not feel handicapped by the lack of modern instruments, for it is possible to make color measurements with a considerable degree of accuracy and precision by very simple means.

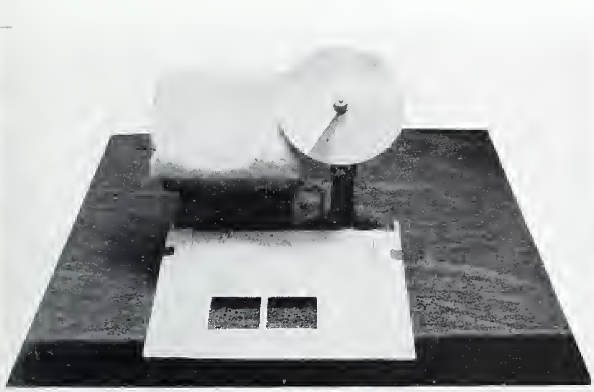

FIGURE 19.—Simple method of color matching. Color disks are spun in juxtaposition to the sample being measured. The use of a neutral gray mask with openings of equal size, one to be placed over the sample, the other over the disks, provides standardization of background and size of comparison fields. The two fields are compared by eye and the areas of disk segments changed until the color of the spinning disks matches the color of the sample.

[17] Large-scale enlargements of the most used portions of these charts are available in packaged form from the Munsell Color Co. for use as graph paper. Full explanation of procedure is given later in this publication.

[18] From (*43*).

[19] From (*47*).

[20] From unpublished conversion charts, Maerz and Paul to Munsell.

[21] From (*22*).

[22] Photocells and tubes may be applied with complete success to spectrophotometric work where a match made by cell will be the same as that made by the eye. This is because the wave length range for spectrophotometry is so restricted that only a brightness match is required. But colorimetric matches are in a different category. No photocell has the same characteristic color response as the normal eye, and no filters have yet been found to adjust cells accurately to visual responses of the normal eyes; therefore, while spectrophotometry has been speeded up and made automatic by use of photoelectric devices, no completely satisfactory photoelectric colorimeter has yet been made. The normal eye is still the best direct color-measuring device.

[23] By Keuffel & Esser Co.

[24] By Bausch & Lomb Optical Co.

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FIGURE 20.—Early disk colorimeter designed to replace spinning of disks by a spinning optical part, and provide for sample and disk illumination within an instrument. This instrument (Keuffel & Esser) provides for measuring an area of 4 inches in diameter behind the black ring. This instrument is in regular use for measuring cotton color.

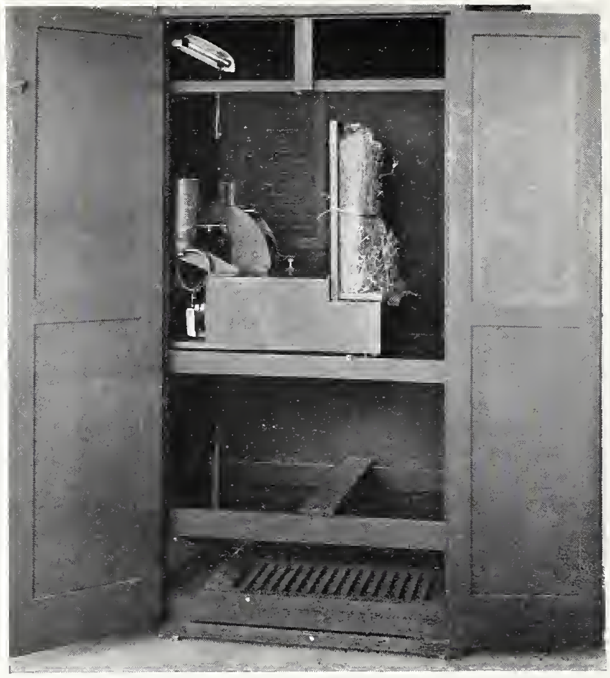

FIGURE 21.—Another early type of disk colorimeter (Keuffel & Esser) designed to measure areas of hay 14 inches in diameter. A side view is shown, with hay sample in place. The entire instrument is enclosed in a small portable darkroom cabinet (note rollers on bottom of platform). After the hay sample is placed in position the double doors are closed, and the operator goes around to the front of the instrument where he works behind a dark curtain that cuts off light from the room in which he is working. This instrument is in regular use today for hay-color measurement.

More thought must be given to standardization of illuminating and viewing conditions without an instrument than with one, of course. But many persons, if they first work by simple methods and learn the necessity for standardizing the various conditions of illumination and observation, might be better able to evaluate the reliability of results with an instrument.

For example, differences in the angle of illumination used cause larger differences in comparing glossy samples than in matte samples. A change in surrounding colors of background can cause differences in results. A difference between black and white uniforms worn by operators in a laboratory will cause significant differences if light reflected from them is not kept from reaching the disk or sample surfaces. Difference in size of areas compared will affect judgment of a color match. All these and many more external conditions that could be controlled can affect judgment of a color match. It is not so easy to control the condition of the eye, although a few simple facts should be stated. A judgment of "match" is not an exact matter. It is made within a tolerance, and the reduction of that tolerance to its smallest size should be the aim of every operator. In matching any sample, say a green-yellow sample, the match points of a novice will vary more in 10 trials than those of an

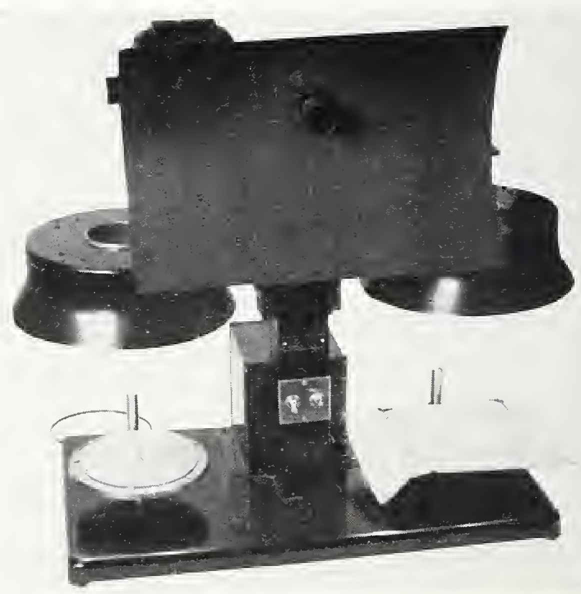

FIGURE 22.—Compact model disk colorimeter (Bausch & Lomb).

experienced observer. Even for the experienced observer there will be a difference in the match when made from the green side as compared with a match made from the yellow side, or a match made from the light side or the dark side, the strong side or the weak side. Three judgments should be made before deciding on any color match, viz:

Are the spinning disks *redder* or *yellower* (or *yellower* or *greener*, etc., depending on the hue) than the sample?
Are they *lighter* or *darker* (value) than the sample?
Are they *stronger* or *weaker* (chroma) than the sample?

As soon as an operator begins to think in three-dimensional color terms and can make quick decisions in answer to these three questions, the ability to change disk areas to make the closest "match" will become rapid and sure. An operator may make matches by trial and error, but such an operator will not work as rapidly and accurately as the operator who makes up his mind what changes should be made before he touches the disks.

The length of time necessary to train individuals to make precise color judgments depends on the observer. Some persons can take an instrument and instruct themselves in a few hours, or have its principles explained and within a day or two make measurements that are as satisfactory as those of a more experienced observer. According to Judd, (*34*):

Precision of setting for a color match is subject to irregular fluctuations (hourly, daily, monthly, and long-time) of obscure cause which are at the same time too large and too consistent to be random variations accounted for by the theory of errors. . . . the task of making many settings for color match of the utmost precision requires a very happy balance between tension and relaxation. . . . Any factor which the observer believes to be important constitutes a distraction that really is important and deserves immediate attention.

Furthermore, the observer must be interested in the observations, must believe that they are important, and must have confidence in his ability to carry the observations to a conclusion without interruption and without altering his pace.

In using the method of spinning disks on a motor several things should be kept in mind:

1. The motor need spin only fast enough to avoid flicker in the disks. About 2,700 r.p.m. should be sufficient, but the speed necessary depends on the value contrast in the disks spun and on the amount of illumination. At low levels of illumination less speed is required than for high levels.

2. Use of artificial daylighting that will produce a color temperature and energy distribution about that of I. C. I. illuminant C is preferable when the data are to be computed for illuminant C. Studies made during the course of the work indicate that incandescent lamps used with Macbeth filters (Corning No. 590) of suitable thickness will provide the nearest practical equivalent to illuminant C. For use in an instrument it is feasible to construct Davis-Gibson liquid filters to produce a still closer representation, but the use of liquid filters is not advised except in specialized work.

3. Disks should be laced together so that they spin in the direction of the motor; it is dangerous to let them spin in a direction against the motor for not only will the air tear the disks, but the flying fragments may result in cut fingers and even cut faces. Back of the disks place a solid, heavy cardboard disk, one that is cut without a radial slit. This will prevent tearing the disks from the back. If, in addition, the disk used for backing is calibrated in 100 divisions and made slightly larger than the 4-inch or 4½-inch diameter disks that are generally used in disk colorimetry, then the areas of disks exposed may be read directly.

As previously noted, it is not necessary to use Munsell disks in disk colorimetry. The usual practice is to do so, however, since they are provided in the best selection of measured colors available for this purpose.

Choice of Disks

The disks chosen for matching a series of cotton colors will differ, of course, from those chosen to match tomato colors. In one case the colors are near whites and grays extending to tinged or yellow-stained cottons that may in a few cases have chromas as strong as Munsell /4. Tomato colors will be darker, stronger colors ranging from yellowish to purplish reds.

Obviously, measurements can be made more quickly of colors for which a single set of disks can be used than for colors that require a different set of disks for each measurement. In grading laboratories, one product is generally graded at a time, and if one set of four disks is selected to measure the entire color range, the work can be reduced to a routine and the measurement of one sample after another can be made as rapidly as the samples can be handled. It is quite usual, for example, to measure 10 boxes of cotton in an hour, each box containing 12 samples, an average of one-half a minute per sample. Such speed can be made only when using a calibrated instrument with one set of disks that covers the entire range. Samples should be prepared in advance and the method of handling should be so well standardized that samples follow one another in rapid succession, almost automatically, in the measuring field. Any necessity on the part of the operator to handle the sample, change the disks, or "change his mind" will extend the time.

Before color measurement can be standardized and made routine procedure for each product, the method of sample preparation and the kind of disks to be used must be determined.

With this in mind, a survey should be made of the limit colors that are to be measured in any one product. In cotton, this means two very light samples (one white, the other creamy), two very dark samples (one gray, the other a deep yellow stain), and two samples showing extremes of hue.

Knowing these limits, an operator *might* make a suitable choice of disks from a chaotic series of disks laid out before him. The methodical procedure, however, is to compare these limit colors to Munsell color chips, either on charts (*45*) or from an index file of chips, to ascertain the range. The result would show that no upland cotton is lighter than N 9.4/, darker than N 7/, redder than 5YR, yellower than 5Y, nor stronger than about /4 chroma, most of the chromas being /1 to /2. Since many samples are very light they will require a large percentage of white to provide a match, and since all the chromatic colors in cotton are

below 9.4/ in value, a choice of the strongest chromas available is made for the chromatic disks in order that only small areas will be necessary in disk mixtures for matching cottons. Therefore, the maximum color in YR and Y will be selected, and YR 6/12, Y 8/12, N9.4/, and N 7/ tried out to measure the series. If it is possible to measure the limit colors with these disks, then all other samples should come within the color range that can be measured by them. In terms of the color solid the colors of these four disks will bound a pie-shaped wedge in the solid that contains all the cotton colors. Disk colors should be chosen to bound a wedge big enough to contain the entire range of colors in any single group of colors to be intercompared, such as those of a single product.

In hay, the colors are greens to browns that generally range between 10YR and 10Y, darker than N 5/, and weak enough in chroma so that a wedge in the color solid bounded by 10YR 5/6, 10Y 5/6, N 5/, and N 1/ will include most of the colors to be measured. Disks of these colors are therefore used as a standard choice in matching hay. Occasionally an artificially cured or very special sample will be greener than 10Y. For such samples, a 10GY 5/6 may be substituted for the 10YR 5/6 in order that the wedge now enclosed may be moved to the green side of 10Y. Or extremely reddish brown samples in clover hay may turn up, in which case 10R 5/6 is substituted for 10Y 5/6, the wedge being shifted to the red side of 10YR. Note the choice of value 5/ for all but one of these disks. When a choice of constant value can be made for three out of four disks the color matching is easier, also the calculation of results, for a change then in the value of a match depends only on the black or N 1/ disk, the others being constant at 5/.

Instead of making a visual choice and then finding by trial and error whether the series encloses a large enough wedge, the colors of the extremes may be obtained (visually by comparison to Munsell charts, or by instrument measurement) and the results plotted on an I. C. I. diagram to find the four points in color space that provide limits for an inclusive wedge of color. Figures 23 to 30[25] are I. C. I. diagrams showing Munsell standard colors in 20 hues plotted on value levels 2/ to 9/. The large circled points have been added to represent regular or special Munsell colors listed in table 2, which the charts show to be limit colors. Since all mixtures of color[26] lie on or between straight lines connecting the colors of the four disks chosen for disk colorimetry, these figures (23 to 30) may be used in making a selection of disks.

For use in grading agricultural products, the colors of which range from the purplish red of beets through reds for tomatoes, and the yellow-reds, yellows, and green-yellows of many vegetables, only the RP to GY portion of these charts has been marked with special colors. Greens, blues, and purples are seldom needed in agricultural work, for most of the greens—even of grass—are nearer to green-yellow than to the green of the Munsell system.

As an example of the use of these charts in the selection of the necessary four disks, consider the cotton colors. Most of them are about 10YR in hue, ranging from 8.5/ to 9/ value, and /1 to /2 chroma, with a few as dark as 7/1 and as strong as 8/3. Since the hue range is not wide, the selection of hues may be YR and Y, one on each side of 10YR to allow for what hue variation there may be. The selection of neutrals will be a white of high value, N 9.4/ (9.6/ would be chosen except that it is very fragile, the surface being powdered magnesium oxide mixed with just enough binder to make it stick to the paper) and N 7/. For yellow-red the YR 6/12 will be selected, since the maximum YR's on the 7/ and 8/ value levels lie towards the neutral point on a line drawn from YR 6/12 to the neutral point, thus indicating that YR 6/12 has maximum power and could be used with neutrals or properly selected values to match the maxima colors on the other value levels. The yellow choice will be Y 8/12 (although the recently developed special 4.5Y 8.4/13.3 might be even better) because the maxima yellows on both darker and lighter value levels lie closer to the neutral point than does Y 8/12. When lines are drawn to connect the four colors on an I. C. I. diagram all cotton colors should lie well within them. If they do not, then the disks have been improperly chosen.

For matching colors of high gloss, as in canned tomatoes, the direction of illumination under which they are matched will make a great deal of difference in the selection of disks. During the early work with tomatoes in several laboratories, a series of special glossy disks were made up, and their use seems to have become standard practice in measuring tomatoes. Regular Munsell papers have a matte or near-matte surface; therefore the direction of illumination on them makes little difference, but it does make a difference for glossy disks and for glossy samples, especially for dark samples. Glossy disks are also much more difficult to match from one production to another, and a match for one set of illuminating conditions will not necessarily hold for another. For example, the special glossy red (No. 2208), yellow-red (No. 2207), and black (No. 2209) when measured (*23*) on the Hardy General Electric Recording Spectrophotometer with the specular component included gives results that vary considerably from results when the specular component is excluded. Re-notations for measurements on the same samples under different conditions are given:

Glossy surface papers for matching tomato colors	Specular component	
	Included	Excluded
Red (No. 2208)	5.5 R 3.6/7.6	7 R 3.1/9.2
Yellow-red (No. 2207)	2 YR 5.6/9.9	2.5 YR 5.5/10.3
Black (No. 2209)	N 2.4/ (PB 0.1)	N 1.1/ (PB 0.1)

Measurements made at the National Bureau of Standards and reported in 1935 (*51*) on earlier productions of these tomato papers, gave even greater dif-

[25] Figures 23 to 30 are based on diagrams originally used in a report from the National Bureau of Standards (*39*).

[26] This is true of *color* mixture, as for mixtures of lights, of light reflected from disks, or of stippled effects in painting; not true of *colorant* mixtures, for each pair of paints or dyes has a mixture gamut peculiar to it and each must be studied separately.

TABLE 2.—*I.C.I. and Munsell notations for limit colors, particularly helpful in choosing disks for use in disk colorimetry of agricultural products.* [Many other colors may also be useful; see figures 23 to 30, and (*39, 23*)]

Munsell book notation	Munsell production No.	I.C.I. Tristimulus values			I.C.I. Trilinear coordinates		Munsell re-notation
H V/C		*X*	*Y*	*Z*	*x*	*y*	*H V/C*
2/value							
RP 2/6	1342	0.0656	0.0440	0.0721	0.3609	0.2421	4 RP 2.4/5.9
10 RP 2/6	1372	.0626	.0416	.0544	.3949	.2621	8 RP 2.4/5.6
R 2/6	1124	.0653	.0461	.0434	.4219	.2977	3 R 2.5/4.8
2.5YR 2/3	1556	.0632	.0538	.0431	.395	.336	0.5YR 2.7/2.6
Y 2/2	1203	------	.0495	------	.3481	.3601	5.5Y 2.6/1.4
GY 2/2	1225	.0414	.0474	.0393	.3233	.3702	6 GY 2.4/2.0
10 GY 2/2	2348	.0352	.0423	.0385	.3038	.3646	10 GY 2.2/2.2
G 2/2	1265	.0286	.0358	.0384	.2786	.3478	7 G 1.9/2.4
3/ value							
2 RP 3.3/15.3	2316	.1706	.0784	.2107	.371	.171	2 RP 3.3/15.3
RP 3/10	1346	.1209	.0743	.1126	.3928	.2413	5 RP 3.2/8.4
10 RP 3/10	1376	.1223	.0735	.0849	.4356	.2621	8.5RP 3.2/8.5
4 R 3.4/10.4	2325	.1479	.0846	.0491	.525	.300	4 R 3.4/10.4
2.5YR 3/6	1886	.1123	.0876	.0380	.472	.368	3 YR 3.5/5.8
10 GY 3/4	{ 633	.0544	.0756	.0483	.3050	.4240	10 GY 3.2/4.5
	{ 1455	------	.0847	------	.3056	.4214	10 GY 3.4/4.4
2.5G 3/4	2144	.0562	.0828	.0591	.284	.418	1.5G 3.4/5.0
G 3/4	1264	.0545	.0803	.0682	.2685	.3956	4 G 3.3/4.8
4/ value							
RP 4/12	2521	.2211	.1372	.2014	.3950	.2451	5 RP 4.3/11.1
4.5R 4/13.1	2299	.2223	.1203	.0552	.559	.302	4.5R 4.0/13.1
R 4/14	2220	.2364	.1330	.0562	.5554	.3126	5.5R 4.2/13.3
YR 4/8	1199	.1685	.1414	.0489	.4695	.3941	6 YR 4.3/6.5
7.5Y 4/4	1876	.1213	.1313	.0533	.397	.429	8 Y 4.2/4.2
7.5GY 4/6	2168	.1032	.1348	.0711	.334	.436	7 GY 4.2/4.9
2.5G 4/6	2147	.0869	.1366	.0906	.277	.435	2 G 4.2/6.6
5/ value							
RP 5/10	1357	.3283	.2301	.2934	.3854	.2702	5.5RP 5.3/9.7
R 5/12	1162	.3212	.1981	.1012	.5176	.3192	5 R 5.0/2.7
8.5R 4.8/14.7	2300	.0320	.1759	.0370	.587	.342	8.5R 4.8/14.7
YR 5/10	1195	------	.2135	------	.4942	.4058	5.5YR 5.2/8.9
10 YR 5/8	{ 612	.2266	.2099	.0507	.4651	.4308	0.5Y 5.1/7.6
	{ 1418	------	.2066	------	.4633	.4293	0.5Y 5.1/7.3
7.5Y 5/6	1879	.1987	.2168	.0590	.419	.457	7.5Y 5.2/6.3
GY 5/8	1234	------	.2117	------	.3711	.4782	5 GY 5.2/6.9
10 GY 5/8	{ 881	.1260	.1910	.0833	.3147	.4772	9.5GY 4.9/7.8
	{ 1460	------	.1887	------	.3100	.4647	9.5GY 4.9/7.3
4.5G 5.5/11.5	2309	.1280	.2491	.1804	.230	.447	4.5G 5.5/11.5
6/ value							
RP 6/10	1362	.4384	.3389	.4388	.3605	.2787	4.5RP 6.3/8.4
R 6/10	1156	.4369	.3236	.2514	.4318	.3198	4 R 6.2/9.7
10 R 5.7/14.6	2302	.4002	.2623	.0458	.565	.370	10 R 5.7/14.6
2.5YR 6/13	1578	.4240	.3250	.0613	.523	.401	3.5YR 6.2/12.5
YR 6/12	2050	.4057	.3326	.0630	.5063	.4151	5 YR 6.3/11.4
10 YR 6/10	1422	.3873	.3595	.0711	.4735	.4396	10 YR 6.5/9.9
Y 6/8	1213	------	.3182	------	.4415	.4643	5.5Y 6.2/8.3
2.5GY 6/8	2196	.2725	.3290	.0647	.409	.494	2 GY 6.2/8.7
7.5GY 6/10	2176	.2355	.3274	.0947	.358	.498	6.5GY 6.2/9.0
2.5G 6/8	2155	.1886	.3047	.1912	.276	.445	2.5G 6.0/9.3
7/ value							
RP 7/8	1366	0.5474	0.4845	0.5937	0.3367	0.2980	4.5RP 7.4/4.9
R 7/8	1166	.5142	.4247	.3906	.3868	.3194	3.5R 7.0/7.0
YR 6.6/13.9	2303	.4726	.3718	.0474	.530	.417	5 YR 6.6/13.9
Y 7/10	1218	.4027	.4205	.0759	.4479	.4677	5 Y 6.9/9.6
7.5Y 7/10	1722	.4030	.4457	.0685	.439	.486	8 Y 7.1/10.2
3 GY 7.5/11.2	2307	.4052	.5079	.0771	.409	.513	3 GY 7.5/11.2
8 GY 7.1/10.4	2308	.3090	.4515	.1451	.341	.498	8 GY 7.1/10.4
10 GY 7/8	{ 635	.3115	.4399	.2359	.3155	.4455	10 GY 7.1 8.3
	{ 1467	------	.4331	------	.3173	.4400	10 GY 7.0/8.0
8/ value							
10 RP 8/6	853	.6712	.6251	.7068	.3351	.3121	8.5RP 8.2/3.6
10 R 8/4	722	.6539	.6115	.5744	.3554	.3324	10 R 8.1/3.7
7.5YR 8/6	1565	.6079	.5792	.3883	.386	.368	7.5YR 7.9/5.1
0.5Y 7.7/13.0	2304	.5750	.5335	.0698	.488	.453	0 5Y 7.7/13.0
4.5Y 8.4/13.3	2305	.6468	.6708	.0745	.464	.482	4.5Y 8.4/13.3
7.5Y 8/10	1710	.5076	.5688	.0763	.440	.493	8 5Y 7.9/11.7
2.5GY 8/10	2205	.5010	.6088	.1096	.411	.499	2.5GY 8.1/11.0
7.5GY 8/8	2185	.4553	.5828	.2857	.344	.440	7 GY 8.0/7.6
G 8/6	1250	------	.5149	------	.2878	.3588	5 G 7.6/4.6
9/ value							
10 YR 9/2	2457	.7182	.7232	.7128	.3334	.3357	8.5YR 8.7/1.6
2.5Y 9/8	1730	.7321	.7401	.3639	.399	.403	2.5Y 8.8/6.5
Y 9/14	1705	.6168	.6597	.0760	.456	.488	6 Y 8.4/13.0
9.5Y 8.8/12.2	2320	.6547	.7476	.1150	.432	.493	9.5Y 8.8/12.2
0.5GY 9.2/10.8	2306	.7193	.8326	.1835	.414	.480	0.5GY 9.2/10.8
Neutrals							
N 9.6/	2213	.9140	.9356	1.0966	.3102	.3176	[1] N 9.6/(G 0.1)
N 9.4/	2212	.8154	.8360	.9288	.3160	.3240	N 9.2/(Y 0.4)
N 9/	[2] 1177	.6993	.7165	.8020	.3153	.3231	N 8.7/(Y 0.3)
N 8/	[2] 1176	.5470	.5612	.6426	.3124	.3205	N 7.8/(GY 0.3)
N 7/	[2] 1175	.4274	.4372	.5119	.3105	.3176	N 7.0/(G 0.1)
N 6/	1174	.2956	.3022	.3597	.3087	.3156	N 6.0/(B 0.1)
N 5/	1173	.1849	.1887	.2236	.3096	.3159	N 4.9/
N 4/	1172	.1145	.1164	.1404	.3085	.3134	N 3.9/(PB 0.1)
N 3/	[2] 1171	.0621	.0632	.0757	.3087	.3145	N 3.0/
N 2/	1170	.0269	.0274	.0329	.3082	.3145	N 1.8/
N 1/	[2] 1169	.0113	.0116	.0150	.2978	.3054	N 1.0/(PB 0.1)
Special glossy colors for tomatoes							
R[3]	2371	.1474	.0974	.0555	.4909	.3244	6 R 3.6/6.3
R[4]	2371	.1261	.0759	.0308	.5416	.3259	7 R 3.2/9.4
YR[3]	2476	.3329	.2529	.0814	.4989	.3791	2.5YR 5.6/10.0
YR[4]	2476	.3152	.2351	.0604	.5161	.3850	2.5YR 5.4/10.6
N 1/[3]	2373	.0102	.0409	.0512	.3039	.3090	N 2.3/(PB 0.3)
N 1/[4]	2373	.0117	.0116	.0179	.2839	.2817	N 1.0/(PB 0.8)

[1] Technically Neutral (N) indicates only colors with 0.0 chroma, but because this would not allow the gray series to be easily identified and segregated, the near-neutrals (usually considered as chromas under 0.5) are indicated as N and the chroma, accompanied by the nearest of the 10 principal hue names, is placed in parentheses after the solidus (/) which follows the value number.

[2] Data for the neutrals were obtained from measurements made at the National Bureau of Standards in 1945 (Report No. 43C–29/45–3). These data differ very slightly from those published in (*39*) which were taken from measurements made in 1936 on papers of these same production numbers.

[3] Calculated from spectrophotometric curves made on the General Electric recording instrument with specular component included.

[4] Calculated from spectrophotometric curves made on the same instrument but with specular component excluded.

NOTE: Data in this table are from several sources and apply only to papers available in 1945. The data from NBS reports (39 and NBS reports to United States Department of Agriculture) and from the Glenn-Killian report (*21*) are given in full to four decimal places for *X*, *Y*, *Z*, and *x*, *y*. The data from the Granville report (*23*) are given to three decimal places for *x*, *y*. The data for a few repaints are from unpublished measurements obtained (under the direction of J. J. Hanlon, later of H. A. Sloviter) at the Philadelphia Navy Yard laboratories; these data are not reported for *X* and *Z*, but may be calculated by finding *z* (which is 100 — *x* — *y*), and calculating *X* and *Z* by multiplying *x* and *z* by the ratio *Y*/*y*.

ferences when measured under diffuse and 45° illumination. Re-notations based on these measurements are:

Tomato disks	Illumination: Diffuse	Illumination: 45°
Glossy red[1]	5.5 R 3.4/8.1	8 R 2.7/11.5
Glossy yellow-red[2]	2.5 YR 5.8/10.9	3.5 YR 5.7/13.2

[1] Called 5 R 2.6/13 (in Atlas notation).
[2] Called 2.5 YR 5/12 (in Atlas notation).

Note that the differences in angular conditions of illumination cause greater color differences for dark samples than for light samples. Note particularly the resulting value differences for the black (2209).

It is always important to have illuminating and viewing conditions standardized, but in order to minimize differences between visual and instrumental results due to this cause, matte-surface disks are recommended in disk colorimetry whenever obtainable. Special care should be taken when measuring glossy samples to see that instrumental illuminating and viewing conditions are the same as those used in inspecting the samples.

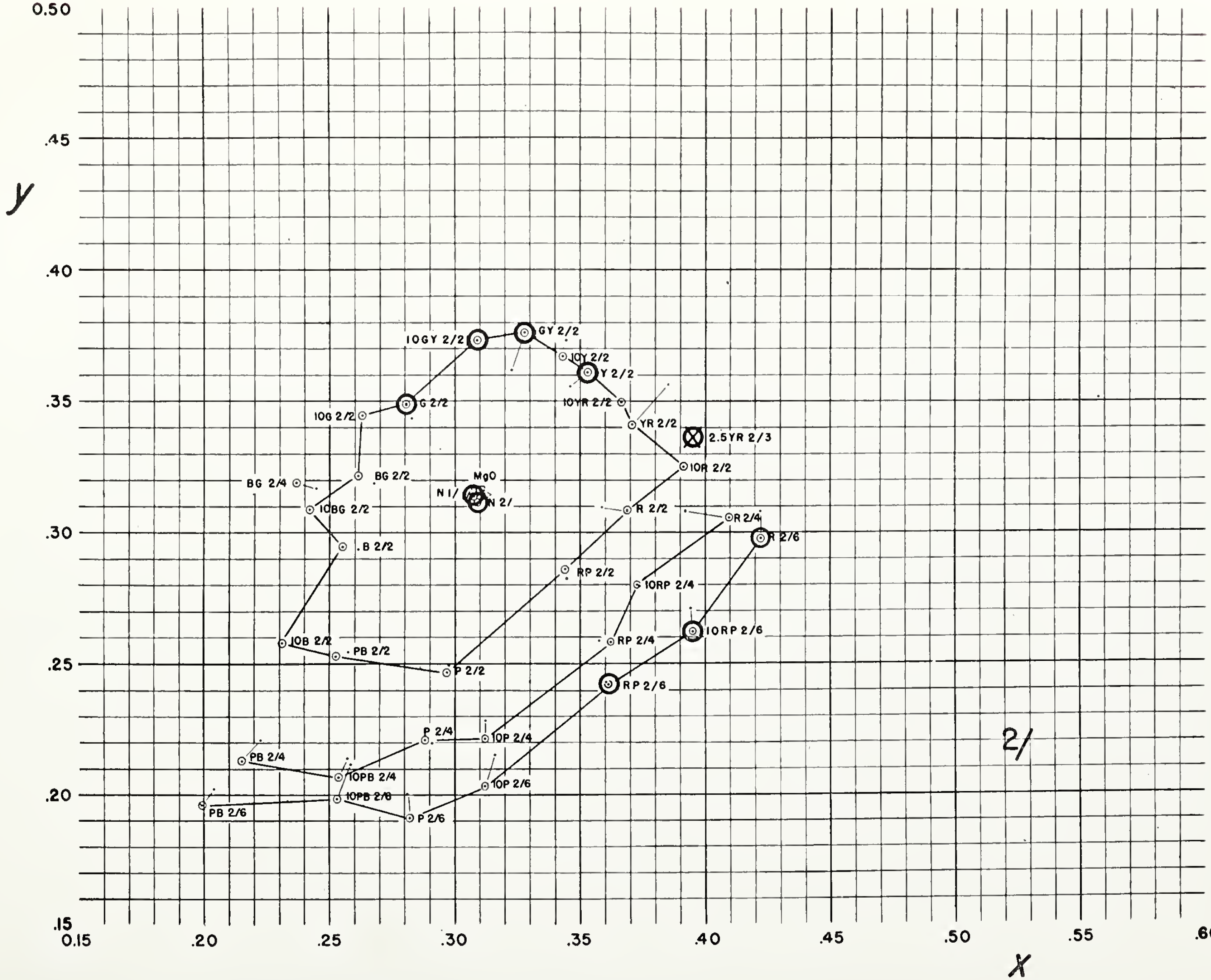

FIGURE 23.—A portion of the I.C.I. chromaticity diagram showing (x, y)-data for illuminant C for Munsell standards in 20 hues for value level 2/. Points enclosed in small circles represent measurements made at the National Bureau of Standards (*39*); points not enclosed represent measurements made at the Massachusetts Institute of Technology (*21*); large, heavy or crossed circles represent colors listed in table 2 for value 2/.

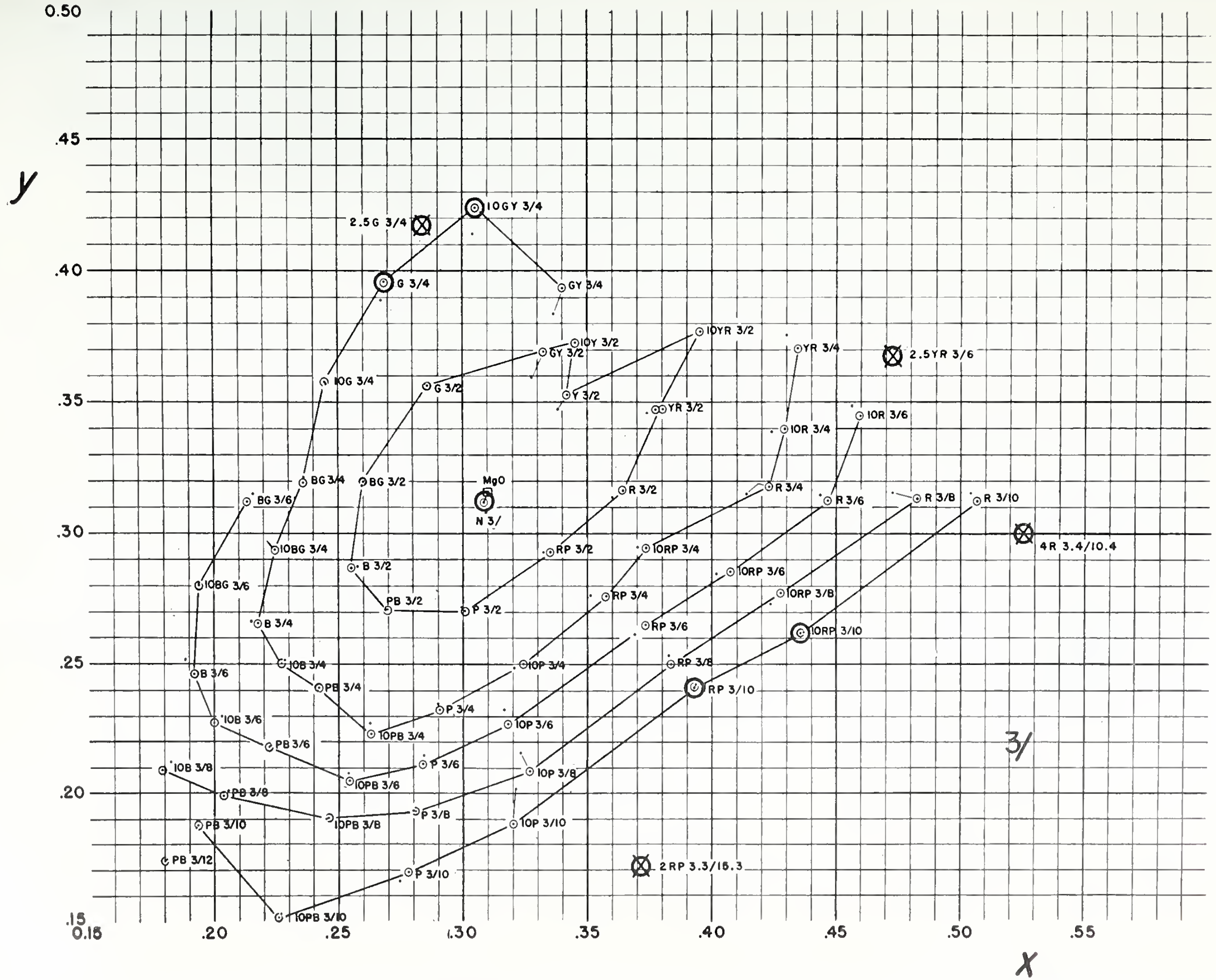

FIGURE 24.—A portion of the I.C.I. chromaticity diagram showing (x, y)-data for illuminant C for Munsell standards in 20 hues for value level 3/. Points enclosed in small circles represent measurements made at the National Bureau of Standards (*39*); points not enclosed represent measurements made at the Massachusetts Institute of Technology (*21*); large, heavy or crossed circles represent colors listed in table 2 for value 3/.

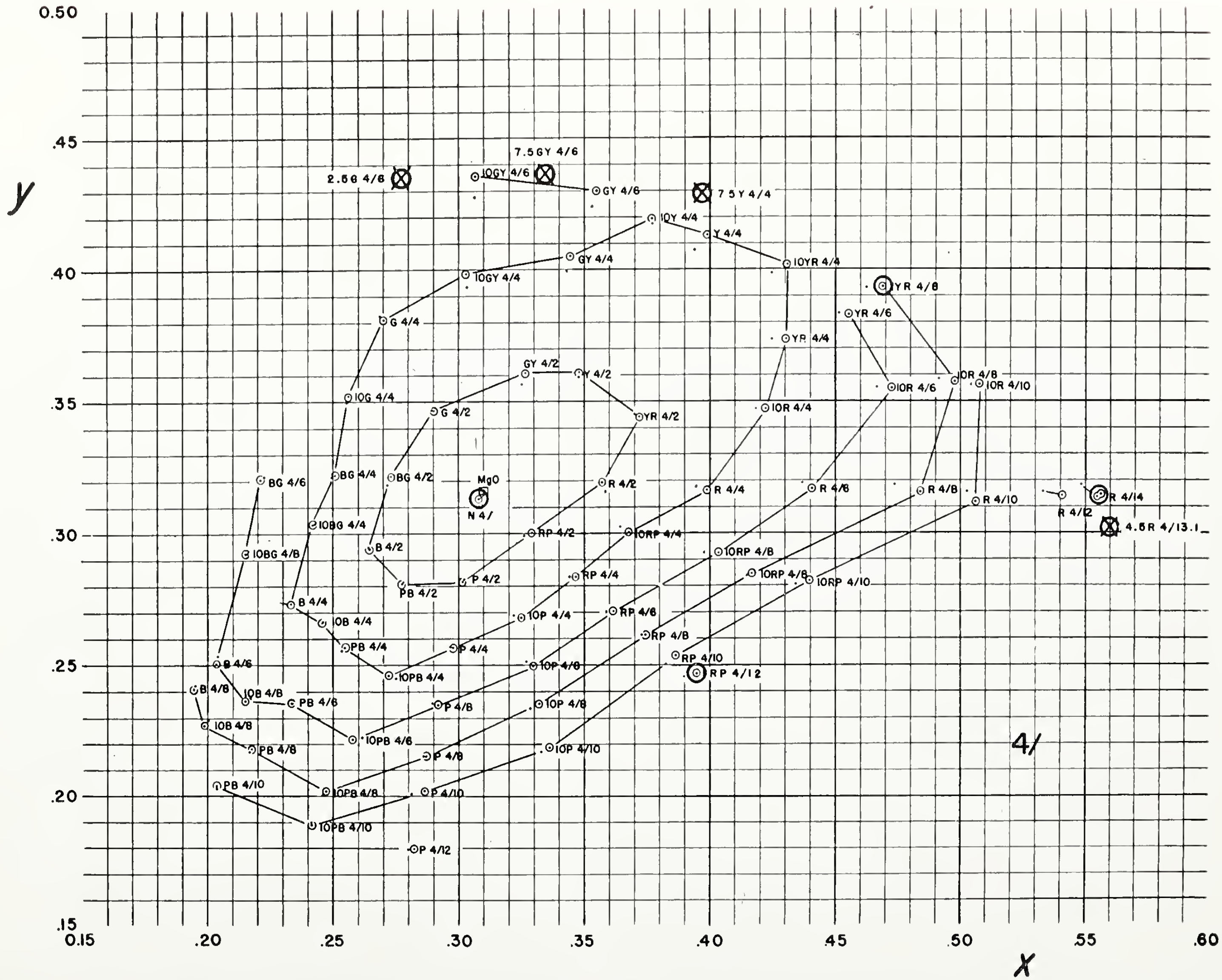

Figure 25.—A portion of the I.C.I. chromaticity diagram showing (x, y)-data for illuminant C for Munsell standards in 20 hues for value level 4/. Points enclosed in small circles represent measurements made at the National Bureau of Standards (*39*); points not enclosed represent measurements made at the Massachusetts Institute of Technology (*21*); large, heavy or crossed circles represent colors listed in table 2 for value 4/.

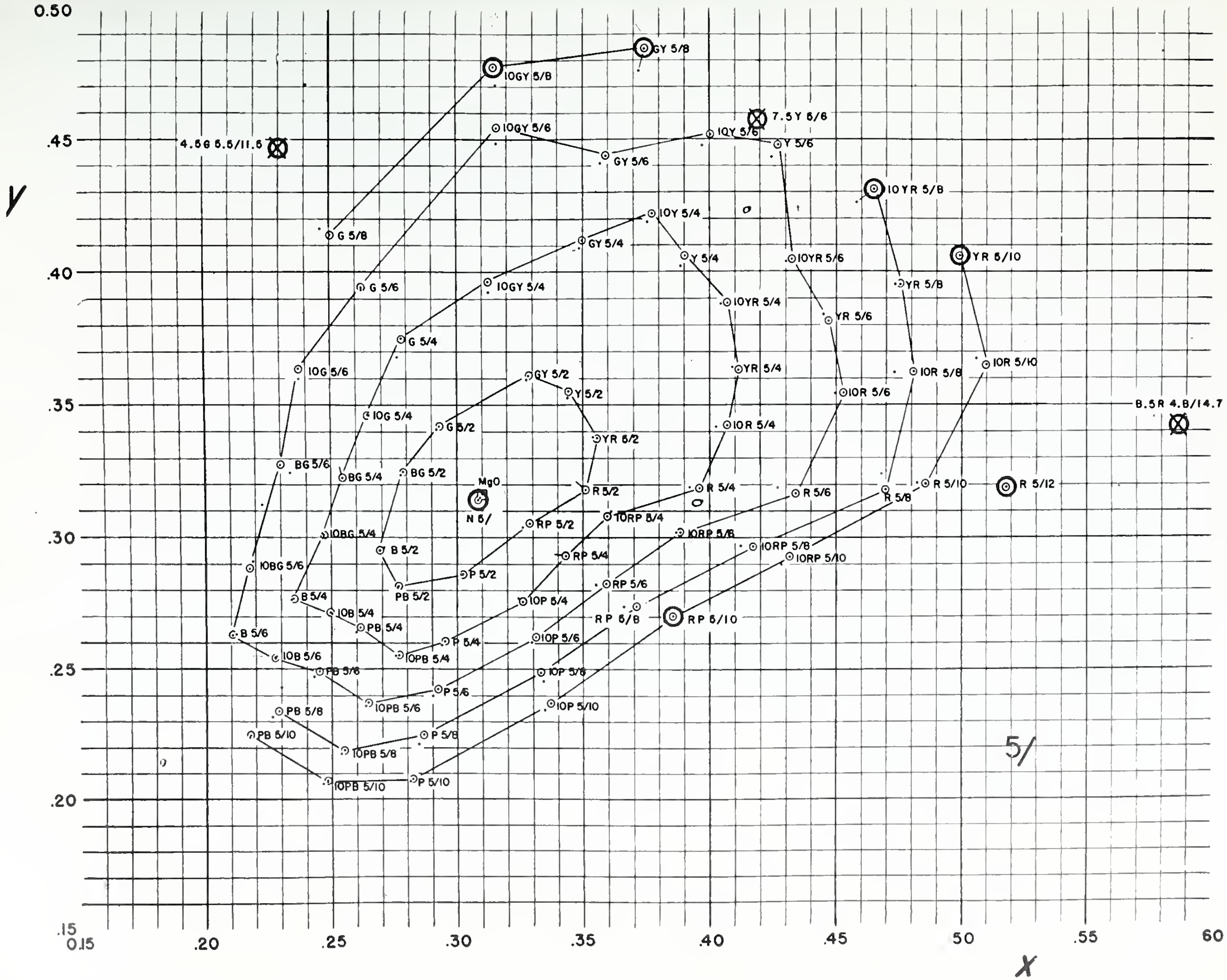

Figure 26.—A portion of the I.C.I. chromaticity diagram showing (x, y)-data for illuminant C for Munsell standards in 20 hues for value level 5/. Points enclosed in small circles represent measurements made at the National Bureau of Standards (*39*); points not enclosed represent measurements made at the Massachusetts Institute of Technology (*21*); large, heavy or crossed circles represent colors listed in table 2 for value 5/.

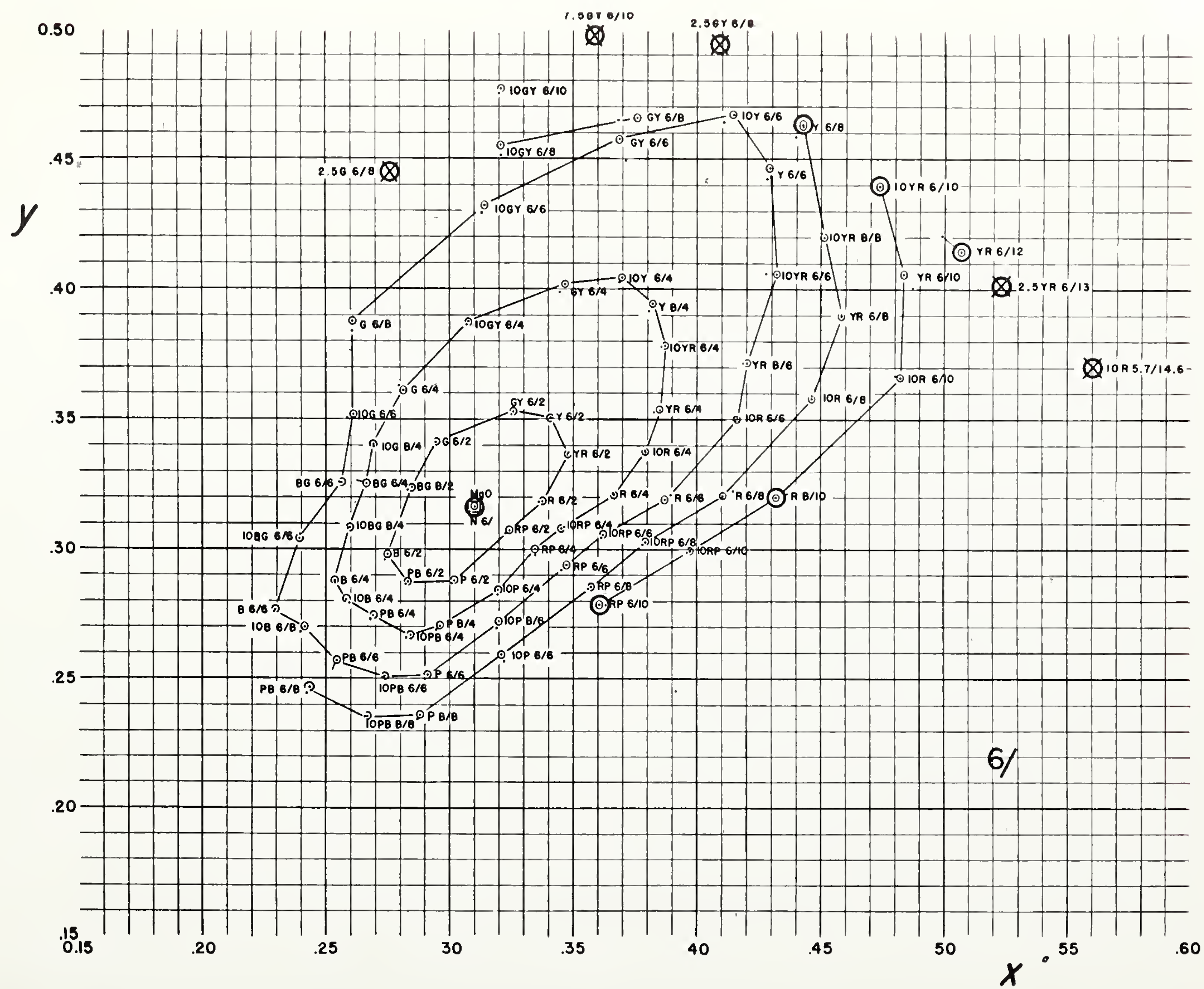

FIGURE 27.—A portion of the I.C.I. chromaticity diagram showing (x, y)-data for illuminant C for Munsell standards in 20 hues for value level 6/. Points enclosed in small circles represent measurements made at the National Bureau of Standards (*39*); points not enclosed represent measurements made at the Massachusetts Institute of Technology (*21*); large, heavy or crossed circles represent colors listed in table 2 for value 6/.

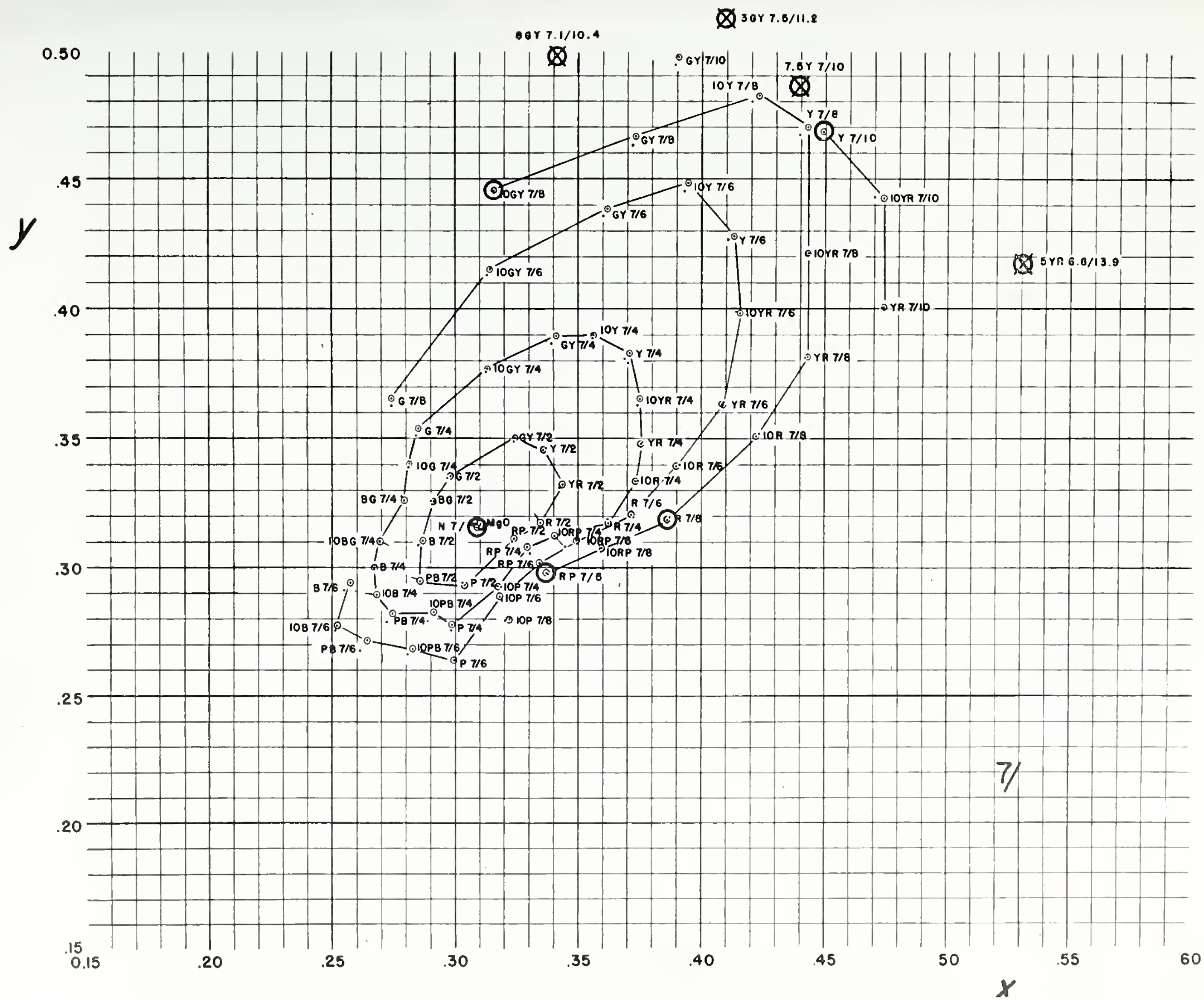

FIGURE 28.—A portion of the I.C.I. chromaticity diagram showing (x, y)-data for illuminant C for Munsell standards in 20 hues for value level 7/. Points enclosed in small circles represent measurements made at the National Bureau of Standards (*39*); points not enclosed represent measurements made at the Massachusetts Institute of Technology (*21*); large, heavy or crossed circles represent colors listed in table 2 for value 7/.

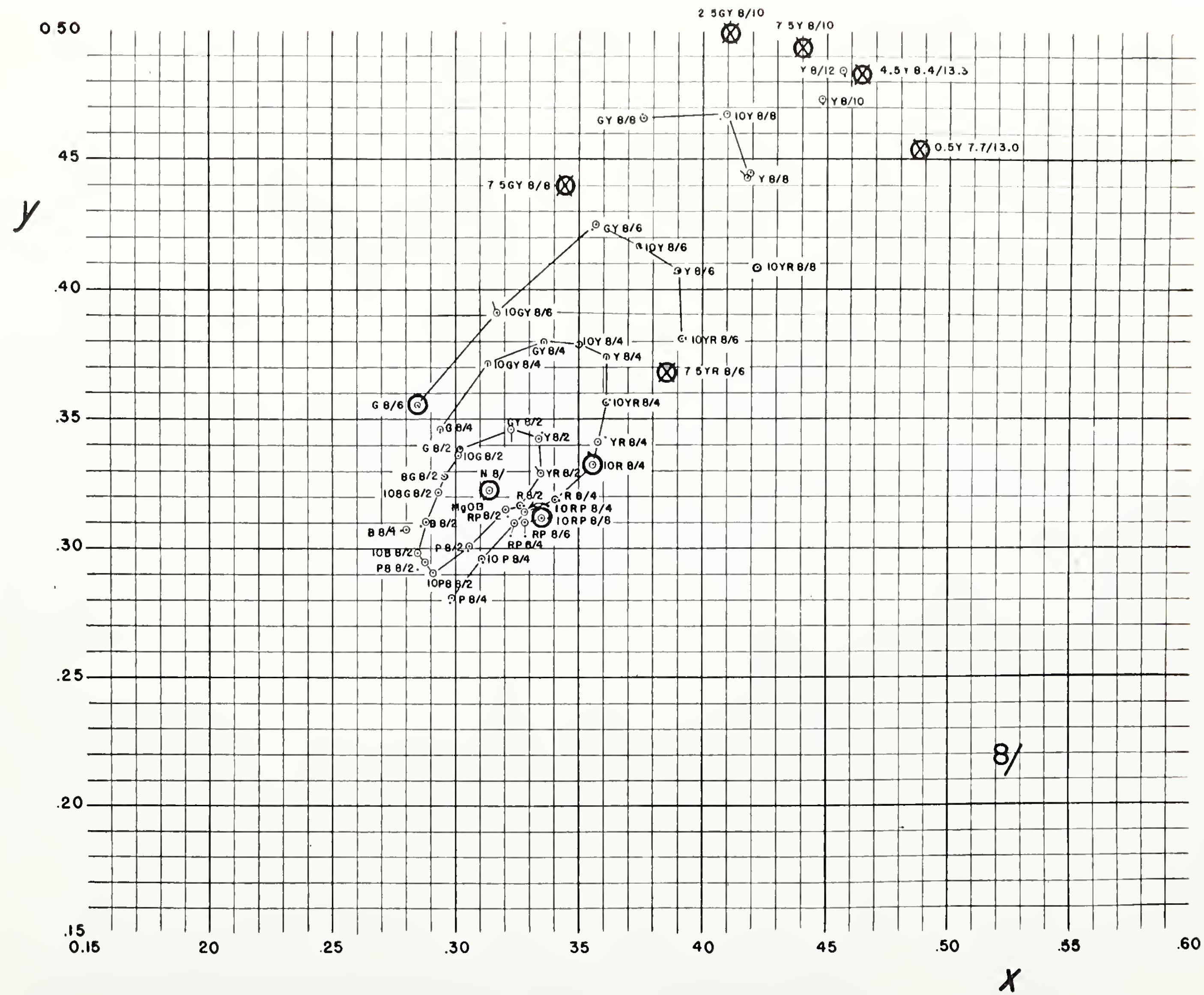

Figure 29.—A portion of the I.C.I. chromaticity diagram showing (x, y)-data for illuminant C for Munsell standards in 20 hues for value level 8/. Points enclosed in small circles represent measurements made at the National Bureau of Standards (*39*); points not enclosed represent measurements made at the Massachusetts Institute of Technology (*21*); large, heavy or crossed circles represent colors listed in table 2 for value 8/.

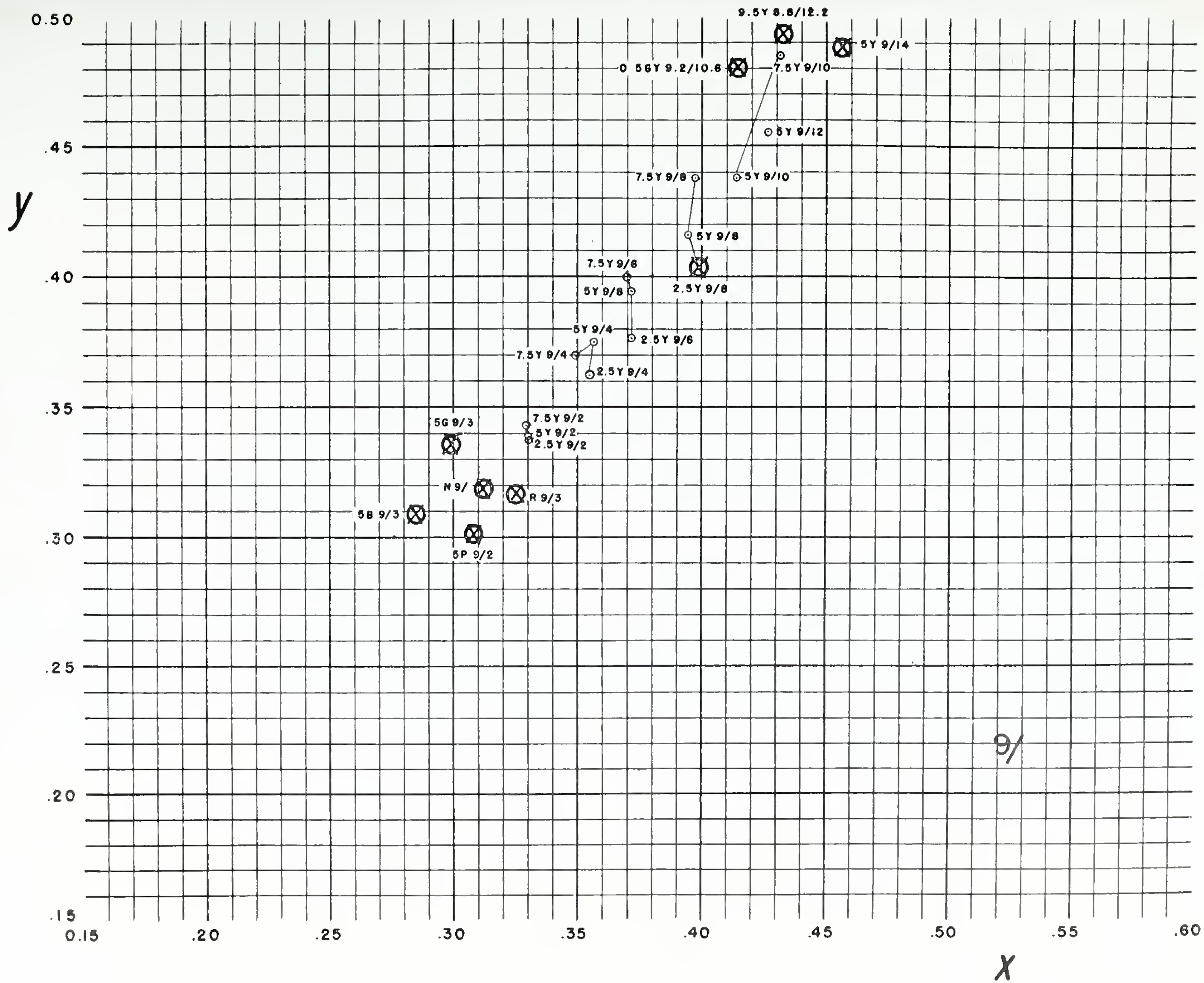

FIGURE 30.—A portion of the I.C.I. chromaticity diagram showing (x, y)-data for illuminant C for Munsell standards for value level 9/. Points enclosed in small circles represent measurements made at the Interchemical Corporation Research Laboratories (*23*); large, heavy crossed circles represent colors listed in table 2 for value 9/.

Once a series of disks is established for use with a given product, it should be followed. If enough work is done with that product, then the preparation of conversion tables is a timesaver. In a few cases conversions from percentages of disk areas may be made directly into grade terms (after careful statistical studies are made); but generally a preliminary conversion to terms of hue, value, and chroma may be made by conversion tables, then the color results read into terms of grade from a second table, or from a diagram.

Table 3 contains a list of a few disk combinations that will work for the products named if the extremes to be measured are no greater than those for which these were selected. Some of the disks listed are lower in chroma than the disks in table 2, but higher chroma disks can always be substituted, although in extreme cases the percentage of a high-chroma disk needed to match a sample may become very small. A check can be made for the disks listed in table 3, or for any other series of disks through the use of figures 23 to 30. An easy method is to make a tracing to show the disk colors that are spotted on the I. C. I. diagram, with lines connecting them, then to spot on the same diagram the limit colors of your product. These limit colors may be in terms of Munsell notations obtained by visual comparison of the samples to the Munsell charts.

Since the charts of figures 23 to 30 already show about half of the available Munsell colors, it will be easy to spot limit colors directly in relation to colors available for use as disks. If limit colors lie outside the lines connecting the disk colors, then disk selections must be made of colors that enclose these limit colors. Lightness of these colors also must be taken into consideration, since a three-dimensional wedge in color space is under consideration. If a limit color is very dark, for example at $x = 0.50$, $y = 0.30$ on the 2/ value level, it could not be matched by use of 4.5R 4.1/13.1 and N 1/ for it would be outside the wedge on this lower value. It would take so much of an N 1/ disk to reduce the value of the disk combination to 2/ that the strongest chroma red that could be matched would plot about $x = 0.45$, $y = 0.30$ on the 2/ value level. On the other hand, if a black of lower value than 1/ could be found, perhaps reflecting as near zero as 0.4/, it would be possible to extend the limits of the wedge and make the match, because in that case the effective chroma of the 4.5R 4.1/13.1 when reduced to 2/ would still be outside the $x = 0.50$, $y = 0.30$ limit needed.

Choice of disks is not always easy, particularly for colors that are very dark, very light, or very strong. If disks could be made from matte-surface materials that reflect nearer to 0 percent light for blacks and closer to 100 percent for whites than those now available it would be very helpful. As for especially strong chroma colors, the Munsell papers are made with pigments ground in oil and selected for high permanence. That is why they are not always as strong as colors available in other or less permanent media. For special problems it may not matter whether the color of disks is fast. In such cases, special disks of strong chroma but nonpermanent colors may be measured and used during the

TABLE 3.—*A few suggested color disk combinations*[1]

Disks 1	Disks 2	Disks 3	Disks 4	Product to be matched
Y 8/12	2.5YR 6/13 or 5YR 6.6/13.9.	N 7/	N 9.4/ for light colors N 5/ for dark colors	Apricots, carrots, pumpkin, mushrooms, pineapple (sliced), orange juice.
Y 5/6	GY 5/8	N 5/	N 7/ for light colors N 3/ for dark colors	Asparagus and spinach.
Y 7/10	3GY 7.5/11.2	N 7/	N 9.4/ for light samples N 5/ for dark samples	Lima beans, grapefruit juice, pears, pineapple (crushed), and sauerkraut.
RP 3/10 or 2RP 3.3/15.3	4.5R 4/13.1	N 3/	N 1/ for dark samples N 7/ for light samples	Beets, pimentoes.
10YR 5/6	10Y 5/6	N 5/	N 1/	Hay.
10YR 7/6	10Y 7/6	N 7/	N 9.4/ for light samples N 5/ for dark samples	Alfalfa meal.
YR 6/12	Y 8/12	N 9.4/	N 7/	Cotton.[2]
7YR 7.4/14 (1744)	7.5Y 9/10 (1718)	N 9.8/[3] (E5462)	N 5/ (1173)	Evaporated milk.
YR 6/12	7.5Y 8/10	N 9.4/	N 3/	Rice.
R 4/14	Y 9/14	N 9/	N 1/	Soils.[4]
R 4/14	Y 6/12 or 10R 5.7/14.6[5]	N 9/	N 1/	Meats.
5YR 6.6/13.9	Y 9/14	N 9.4/	N 7/	Beef fat.
2.5YR 6/13	Y 6/8	N 6/	N 1/ for most colors N 9.4/ for very light samples	Tobacco.

[1] Disks of these notations, or any notations in the regular Munsell books in addition to many special colors, may be obtained from the Munsell Color Co., Inc., 10 East Franklin Street, Baltimore 2, Md.

[2] The cotton work in United States Department of Agriculture laboratories was standardized in 1928 on Munsell Atlas papers YR 6/8, Y 8/9, N 9.4/, and N 7/, and has not been changed.

[3] Not a regular Munsell color, but one furnished through the Munsell Color Co. that has promise if it remains permanent.

[4] Soil colors for standard use selected in 1927 were from the Munsell Atlas papers. The above selection matches a wider color range in papers now available, but for anyone who wishes to use the old soil series it is: Atlas R 4/8, Y 8/8, N 9/, and N 1/.

[5] For a restricted beef color range.

period in which they retain the color represented by the measurement; or other materials may be used if disks can be cut from them. Preferably they should have a matte surface, with I. C. I. data available for them.

It is also preferable that I. C. I. data for any 4-disk selection be obtained in the same laboratory and on the same instrument.[27] Accuracy of absolute as compared with relative results by disk colorimetry will depend on the accuracy of the primary measurements made on the disks that are used. Use of a spectrophotometer for such measurements is no guarantee that the results will be accurate, for spectrophotometers must be kept in very careful calibration, both for their wave length and photometric scales, and the data must be calculated with care if results are intended to be in absolute terms.

It is possible to measure colors of very strong chroma that are outside the range of Munsell or other available disks if they are in flat surfaces as in textiles or paper, for then a disk may be cut of the sample to be measured and substituted for a known disk, this series of disks being matched to a known sample of weaker chroma.

Or, when disk matching is done directly by spinning disks on a motor, a 2½-inch disk may be cut of the sample and mixed with a 2½-inch neutral disk—half and half if necessary—and this combination used as the sample. After obtaining a match in the usual manner, the I. C. I. values of the unknown may be obtained if 50 percent of a neutral disk was used by subtracting 50 percent of the I.C.I. values of the neutral that was used and multiplying the remainder by 2. With the newest type of disk colorimeter provision of this sort is made for mixing colors on both the sample and the disk side of the instrument. Therefore, by adding known percentages of a neutral disk to an unknown sample, the color of that unknown sample may be obtained even if it is a much stronger color than any Munsell standard paper.

Conversion to Munsell Notation

Although use of Munsell disks in disk colorimetry does not necessitate use of the Munsell notation, the Munsell notation (*50*) seems the logical one to use in connection with grading problems. Scales of hue, value, and chroma are in steps that are judged equal to the eye; therefore visual interpretation of grade intervals and color differences may be directly related to diagrammatic representation in terms of hue, value, and chroma scales and laboratory measurements may be directly interpreted by the inspector in terms of his own experience.

For commodities measured in terms of four disks, conversion charts may be prepared once the range of disk areas is known. But first the conversion must be made for each measurement.

In the discussion of the use of the I. C. I. method in the chapter on disk colorimetry an example was used that employed 10 percent of a yellow-red disk, 10 percent of a yellow disk, 20 percent of a white disk, and 60 percent of a gray disk to match the color of a cotton sample. Those disks were Munsell YR 6/12, Y 8/12, N 9.4/, and N 7/. The I. C. I. data for a daylight match (illuminant C) for these colors were obtained from table II of a report of the National Bureau of Standards (*39*). The result of spinning 10 percent of YR 6/12 ($X = 0.3962$, $Y = 0.3241$, $Z = 0.0617$), and with 10 percent of Y 8/12 ($X = 0.5374$, $Y = 0.5706$, $Z = 0.0697$), 20 percent of N 9.4/ ($X = 0.8119$, $Y = 0.8311$, $Z = 0.9455$), and 60 percent of N 7/ ($X = 0.4337$, $Y = 0.4433$, $Z = 0.5285$) under illuminant C resulted in a color specification for the cotton sample of $X = 0.5159$, $Y = 0.5217$, $Z = 0.5194$, the fractional data being $x = 0.3313$, $y = 0.3351$, and $z = 0.3336$.

To convert to the Munsell notation, refer to table 1 (p. 11) and figures 8 to 16 (pp. 12-20) and follow the instructions of the O. S. A. subcommittee report. First the value is read from table 1, then the hue and chroma are spotted on adjacent value-level charts. For the cotton sample,

$Y = 0.5217$, $x = 0.3313$, and $y = 0.3351$:

1. From table 1 it is found that for $Y = 0.5217$, Munsell value (V) is 7.59/. For many cases this can be rounded to 7.6/.
2. Since $V = 7.6/$, Munsell hue and chroma will be found by interpolation between the charts for values 8/ and 7/, figures 15 and 14. On figure 15 for $x = 0.3313$, $y = 0.3351$, the Munsell hue is 10YR (hue is usually read to the nearest 0.5). The chroma is /1.4. On figure 14 for $x = 0.3313$, $y = 0.3351$, the hue remains 10YR and the chroma falls about /1.3.
3. Since 7.6 is 0.6 of the distance between 7/ and 8/, the interpolated hue will be that of value 7/ plus 0.6 of the difference between the hues read from values 7/ and 8/. Since they are the same, the resulting hue is 10YR. Obviously, in this case, the interpolation formula was unnecessary, for hue could be read by inspection. The interpolated chroma will be chroma at 7/ plus 0.6 of the difference between chromas read from the 7/ and 8/ charts. Since the chroma on the 8/ chart is /1.4 and on 7/ it is /1.3, the interpolated chroma will be $1.3 + [0.6(1.4 - 1.3)] = 1.4$
4. The complete notation for the cotton sample, under illuminant C, is 10YR 7.6/1.4.

Munsell hues at high values are generally so little different at adjacent value levels that they can be read by inspection. Chroma, however, varies considerably at all levels, and interpolation will usually be required. The hues at the lower values—particularly in the red and red-purple region—will vary considerably between adjacent value levels.

A protractor, illustrated in figure 31, is convenient

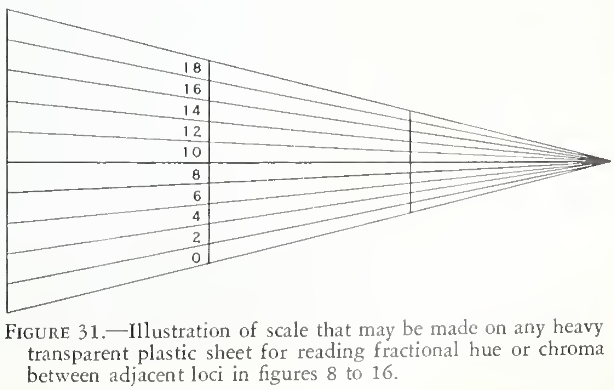

FIGURE 31.—Illustration of scale that may be made on any heavy transparent plastic sheet for reading fractional hue or chroma between adjacent loci in figures 8 to 16.

[27] This is advisable even when using the data published in (*39*), (*23*), and (*21*). There is bound to be some discrepancy in the measurements in different laboratories, and the discrepancies seem to be at a maximum for samples of low Munsell value.

for reading between the hue and chroma loci. It can be made of transparent cellulose and ruled in ink.

The reverse conversion may be made from Munsell notation to I. C. I. within the tolerance with which the Munsell notation is given. The subcommittee report gives the following example, to obtain I. C. I. (Y, x, y) equivalents for 5R 2.4/9.9:

1. From table 1 (p. 11) it is found that for $V = 2.4/$, I.C.I. $Y = 4.28$ percent.
2. Since $V = 2.4/$, x and y will be found by interpolation between the charts for values 3/ and 2/. On value 3/ for 5R 3.0/9.9, I.C.I. $x = 0.548$ and $y = 0.303$. On value 2/ for 5R 2.0/9.9, I.C.I. $x = 0.553$ and $y = 0.264$.
3. Since 2.4 is 0.4 of the distance from 2/ towards 3/, the interpolated chromaticity (x, y) will be that of value 2/ plus 0.4 of the difference resulting when the chromaticity read from 2/ is subtracted from that of 3/. Since x on 2/ is 0.553 and on 3/ is 0.548, the interpolated x will be
$$0.553 + [0.4(0.548 - 0.553)] = 0.551.$$
Similarly, the interpolated y will be
$$0.264 + [0.4(0.303 - 0.264)] = 0.280.$$
4. The complete notation for the sample is
$$Y = 0.043 \text{ (or 4.3 percent)};\ x = 0.551;\ y = 0.280.$$

The effect of the use of this smoothed system on the notation of the samples in the Munsell book is shown in table III of the O. S. A. subcommittee report (*47*) in which revised designations are given for all the Munsell samples for which colorimetric data have been published (*39, 23, 21*).

The fact that the colors represented in Munsell chips depart from the smoothed data, although in most cases by relatively small color tolerances, is to be expected. In the method of disk colorimetry, where I. C. I. data are used for computing the disk mixtures, it does not matter how far off from the smoothed system the color is. But if the result is to be looked up in the Munsell charts to compare with the nearest color, then the re-notation of the color chips on the chart should be known. For example, a color measured by disk colorimetry may result in a notation of 10YR 7/6.3. To ascertain what this color looks like, an operator will expect to find that it lies between chips representing 10YR 7/6 and 10YR 7/8. But it so happens that the chip representing 10YR 7/6 is off by a chroma tolerance of 0.3, so that the chip itself is 10YR 7/6.3. For such comparisons, the re-notations for the color chips should be available.

Likewise, when visual comparisons are made directly to the Munsell charts it is necessary—if comparisons are to be made to the notation of the smoothed system—that color comparisons be made in terms of the re-notations of the color chips used, not in terms of their book notations. If the book notations are used, they should be noted as such or corrected to re-notation where there is doubt of meaning. For example, a specification of YR 6/12 leaves doubt as to the tolerance, in which case the book notation may be sufficiently close. But a specification of 5.0YR 6.0/12.0 would make it necessary, when comparison is made with the book sample, to know the specification of the YR 6/12 chip to a close tolerance. The re-notation of this chip is 6YR 6.2/11.5—close enough to use as YR 6/12 for some purposes but not close enough when precise specification is required.

APPLICATION OF DISK COLORIMETRY TO GRADING PROBLEMS

Sample Preparation

With most colorimetric instruments the area of a sample that can be measured is small, and generally it must be homogeneous. Often it must be measured in a vertical position. With disk colorimetry this can be remedied, depending on the method or instrument selected for use.

Use of a disk spinning motor with the sample directly compared with the disks, as shown in figure 19, limits comparison to materials that are reasonably uniform in color, and to areas that are somewhat less than half the disk area in diameter (in order to mask off equal areas for comparison of sample and disks).

In the early model disk colorimeter the size of field could be varied from areas just under 1 inch up to 10 or more inches in diameter. One of the purposes for which the instrument was designed was to take a slug of hay directly from the bale, place it in a container large enough to hold the complete slug (about 15 by 15 inches), and measure an area large enough to be representative. Since hay color is anything but homogeneous the image on the cube has been purposely set out of focus, and an image of the cube is used in the comparison field on the sample side so that it usually gives as uniform a color as the disk side. This type of instrument, although no longer available commercially, is still used for both hay and cotton standardization, the sample field for cotton being reduced to about 4 inches in diameter—the largest size that could be applied to measurements of samples in the Universal Cotton Grade Standards.

The most recent model disk colorimeter, although it will not take a sample 10 inches in diameter, will take one 3 inches in diameter. In it the sample as well as the disks are scanned by a moving optical part. The illumination on the instrument may be used either as near-diffuse or directional by a change in position of reflectors provided with each of eight small lamps (four on the sample side, four on the disk side).

With any method of colorimetry, disk colorimetry in particular, the method of sample preparation is about one-half of the job. When a flat, matte, opaque surface is to be measured, the problem is relatively simple. Cut a sample of sufficient area to be measured, put it up against the disks (a disk 2½ inches in diameter may be spun directly against 4- or 4½-inch disks) or put it in place on a disk colorimeter, and match it.

Unfortunately, few samples are as simple as that to handle. Sometimes when a surface is flat and matte, it may not be opaque. Then the problem is to select a standard method of backing the sample. Sometimes enough thicknesses of the material are used so that the measurement will remain the same whether backed by black or white.

With raw cotton, the surfaces of samples are generally prepared to a reasonable semblance of the surface used in the standards with which they are compared. Even this is not a flat surface; therefore, the brightness

measurement depends on what is called cotton "preparation," and there will be a small but significant difference between the same cotton when measured with rough and with smooth preparation. Sometimes this difference is exactly what is being measured, as in cotton ginning studies where it is desirable to know the effect of loose and tight gin-roll settings on the cotton preparation. Measurements on paired samples by loose and tight roll on several hundred cottons showed significant differences in terms of Munsell value. This did not mean that the cotton fiber color was different in the paired samples but that the surface appearance of the paired samples was different.

With hay, the surface measured is the surface of any slug as it is taken out of a bale of hay. Again, this is anything but uniform in color. If the greater part of the green happens to be in the center of the slug and all the brown around the edges, then measurement in the disk colorimeter will be the average color of the area measured.

Some samples, as in processed foods,[28] either must be pulped to give a uniform surface for measurement, or enough different areas must be measured to give a good statistical average for the color of the whole. In measuring canned peaches, for example, parts may appear glossy, owing to their rounded surfaces. Therefore, it may be better to measure very small areas that can be brought into a small flat field (perhaps indicated by a wire frame) and average several measurements than to attempt to average a large area in which there are many high lights from glossy areas. Or, if a thin glass plate is used to press the surface of the fruit to a level with the liquid, then a large area can be measured at one time. Slight changes in uniformity of angle as well as in amount of illumination become a problem when glossy surfaces are measured, so the operator must see to it that the instrument illumination is kept in careful calibration. One man solved the problem of measuring the rounded surface of apples by using a die to cut ¼-inch samples from different parts of the apple, then fitting those samples together to give a flat field about 1-inch square.

Liquids require special containers if they are to be measured in a vertical position, and transparent or translucent liquids must have a standard backing, whether measured in a vertical or horizontal position. In some cases, the surface may be measured, as of opaque and translucent samples, the depths used for such purposes being great enough so that there is no change in surface color with increase of depth. Transparent liquids may be treated as if they were filters, the measurements being made of a standard color—generally white or a neutral gray of suitable lightness—placed behind a standardized thickness of liquid filters. With containers that have bottom or sides of optical glass, a paper of standard color may be viewed with a standard depth of liquid placed between it and the eye of the observer. Or, the bottom or walls of an opaque container may be standardized for use in place of such a background.

A very useful container for measuring 1-inch-diameter areas of powdered drugs and chemicals, developed by Kelly (*38*), is illustrated in figure 32. It is useful for measuring many other products, as precise measurements can often be made with a thin glass cover for the surface. However, when a surface can be scraped reasonably flat, as for soil or grain samples or for many processed foods, and the sample measured in a horizontal position, this method is generally preferable.

Glass petri dishes provide good containers for measuring some samples, but no supply of containers would suit all the many products that need measurement. An understanding of what is required from the color measurements, together with some ingenuity in providing a

[28] Of considerable interest is a recent discussion of color investigations in canned foods by A. Kramer and H. R. Smith of the National Canners Association: Preliminary investigations of the measurement of color in canned foods. Food Research, in press.

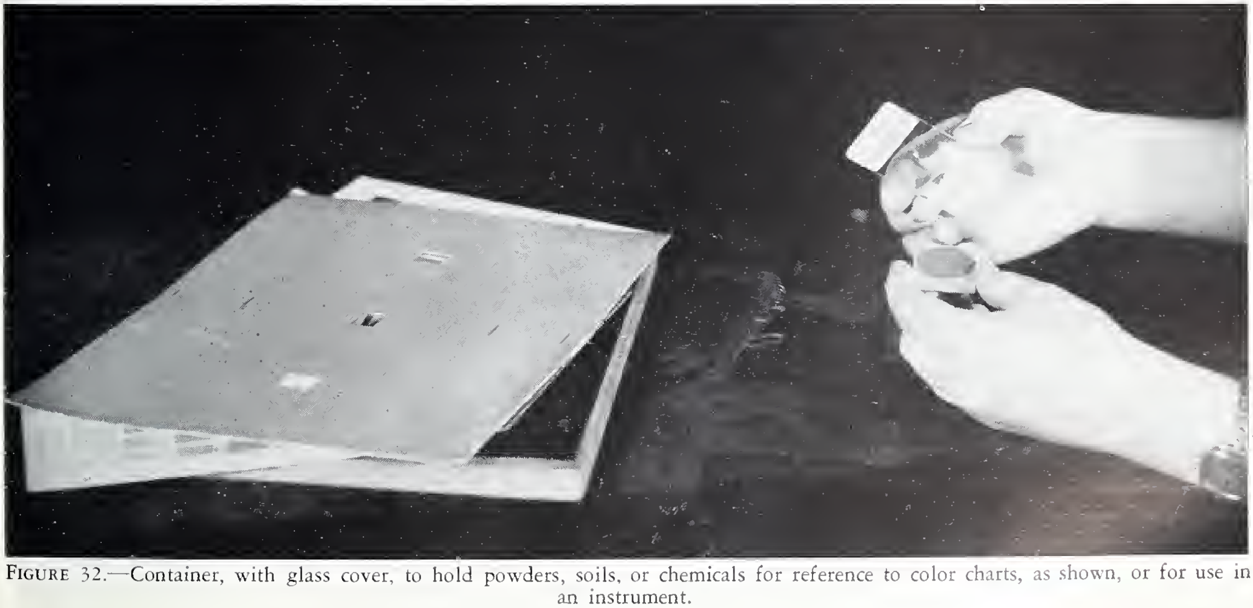

FIGURE 32.—Container, with glass cover, to hold powders, soils, or chemicals for reference to color charts, as shown, or for use in an instrument.

container that can be adopted as standard for the product, is necessary. In measuring tomato pulp, those in charge of the work found that a container painted black on the inside worked very well, and since the samples did not always reach the same level, a supply of shot was kept at hand to drop into the container until the surface reached the proper level. An arm is provided on the new disk colorimeter for raising and lowering the sample platform so that the surface measured may always be at the level for which the illumination calibration was made, but where no such device is available, a supply of shot, or even a few wooden blocks, may do.

Once a method of sample preparation is adopted it should be followed in all routine work. It is a good thing to remember that the color measured is the color of whatever surface is measured; if tomatoes are pulped, it is the color of the pulp that is measured, not the color of the original tomato. And if the pulp has high lights included in the measurement, the results will not agree with the color obtained by visual inspection of the pulp, since the inspector avoids angular conditions that yield high lights. If the illumination in the instrument is not near to a daylight substitute a visual inspection of the color may not agree with instrument measurements. Some instruments are equipped with a daylight filter that is meant to bring the effective illumination to 6,500° K (*51*). For comparison with results calculated for I. C. I. illuminant C (about 6,700° K), this is very good. For comparison with results of preferred conditions of illumination in grading work, it could be up to 7,500° K.

Preparation of Conversion Data

For grading work it is seldom that a color measurement is wanted by itself. Usually color measurements are used to study the relations between samples, and between sample and standard. If standards are already available in material form, then several sets of them may be measured to obtain a good average for each grade. Or, if standards are not available in material form, then a representative series of samples should be measured for which inspectors have given their grade or color estimates. The series should be sufficient to provide an adequate statistical sample of the color of the product. It is better to have too many than too few samples.

In the first case, after several sets of standards are measured, it is a simple matter to plot them to discover what their color relations may be. Since color is three-dimensional, no two-dimensional diagram will uncover all its relations. But if hue is plotted (horizontally) against value (vertically), and chroma is plotted (horizontally) against value (vertically), the significance of the color relations to grade should immediately become apparent. When samples representing cotton grades are plotted in this way it is apparent that hue has little relation to grade but that the samples distribute themselves in a quite regular manner on a value and chroma chart.

Figure 33 is a diagram taken from Service and Regulatory Announcements No. 150, Revision of Standards for Grade of American Upland Cotton, by the United States Department of Agriculture, issued March 1936. It shows a color plot of representative samples taken from the 1934 cotton crop against a diagram representative of the color relations (in Munsell value and chroma) of the grade standards in effect in 1934. The 1934 crop survey as shown against these standards indicates that the bulk of the crop in the high grades was considerably whiter than the standards for the white grades. This was not in accord with grading practice, and this chart shows the reason for changing the color of the standards in 1935. Standards for the high grades by 1935 were much yellower than the crop, and since this was not unusual for the 1934 crop, but was happening each year, it seemed time to change the standards. By law a year's notice must be given for any change in the cotton grade standards; therefore, the new standards (in physical form) adopted by the International Conference in 1935 became effective in 1936. The grades were changed enough so that the relation of current crops to the standards became as illustrated in figure 34.

For some other commodity, perhaps a hue-value, or hue-chroma, relation will clearly show the color relation between grades. In a few cases it may take all three color attributes to discover it. One very useful method, when a direct plot of results is not sufficient, is to apply the statistical method of multiple curvilinear correlation (*12*) to measure the relation of the three color attributes hue, value, and chroma, to grade. Such correlations were obtained for the color of the white cotton standards of 1936. The result showed a total correlation of $P^2 = 0.97$ for hue, value, and chroma against grade, with hue showing little or no effect, the result being almost entirely due to value and chroma.

Another and quite different grading problem is one in which standards are not available in physical form, but only in word descriptions. Such a case gave concern in the 1920's to those in charge of developing standards for grading hay. Standards in physical form were an impossibility because hay color does not remain the same from year to year; it changes its appearance too rapidly to be used as a standard. Although color is only one factor in grading hay, it is an important one. Descriptions of United States hay standards (*74*) use the term "percent natural green color" to provide a scale representing the amount of natural green color in field-cured hay as a percentage of green color of hay produced to receive no discoloration from maturity, sun bleach, dew, rain, or other damage. Green color in hay does not mean a brilliant green; it means the green color natural to hay that is produced and cured under favorable conditions. The term 100-percent green color is represented by a different color for different hays. Alfalfa hay, for example, is much greener in its most desirable condition than is the greenest clover hay of high quality.

In order to standardize the system employing "percent natural green color" as one of its specifications, estimates by inspectors for various "percent natural green color" grade specifications were correlated with color measurements. There was high correlation, most of it due to hue. To establish accurate hay "grade conversion"

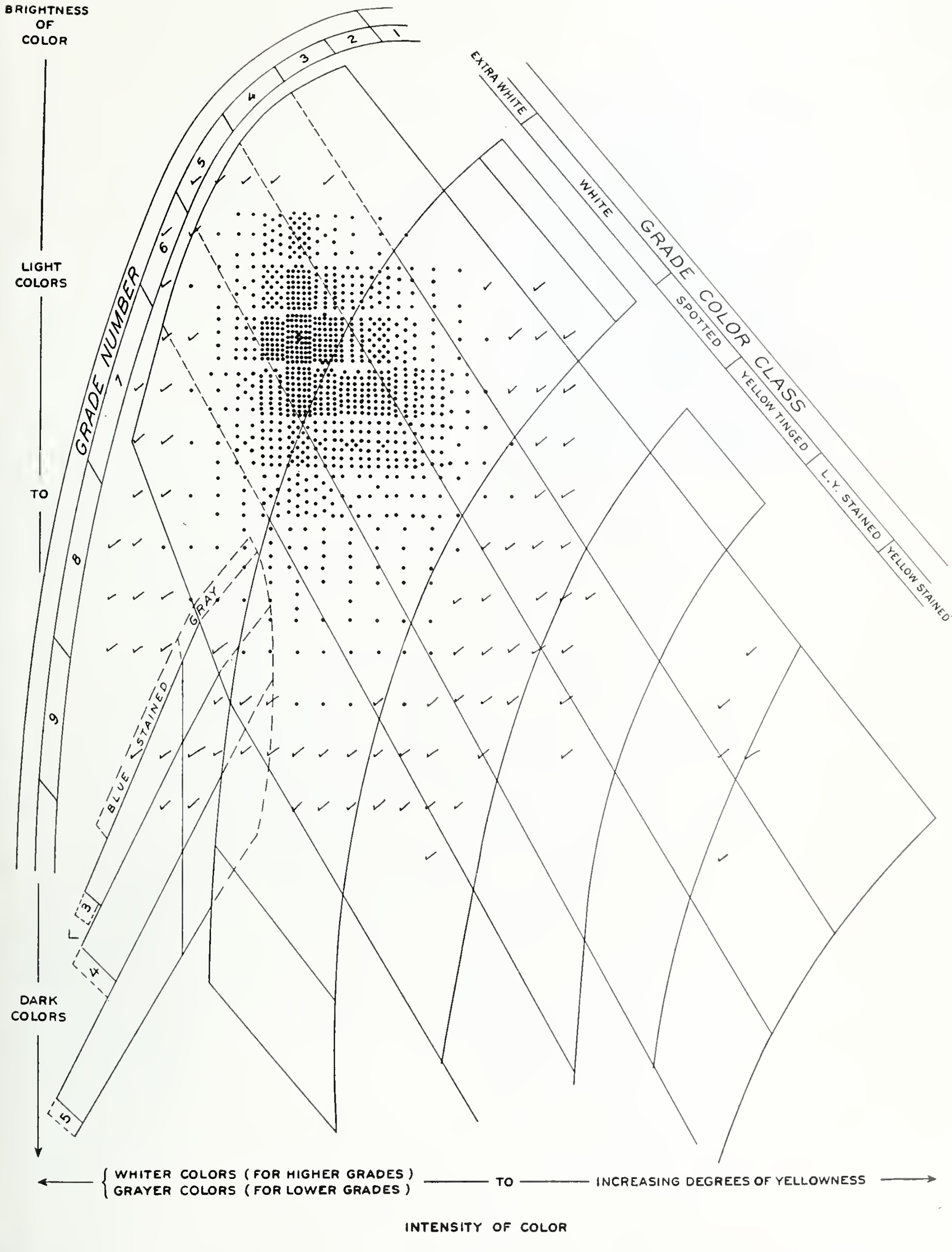

FIGURE 33.—A color plot of representative samples of the 1934 cotton crop shown against a diagram representative of the color relations of the grade standards in effect in 1934 (Munsell value vertical, Munsell chroma horizontal). Each dot represents 0.1 percent of the samples measured; checks represent less than 0.1 percent. The 1935 crop survey as shown against these standards indicates that the bulk of the crop in the high grades was considerably whiter than the standards for the white grades. Since this was not in accord with grading practice this chart shows the reason for changing the color of the standards in 1935.

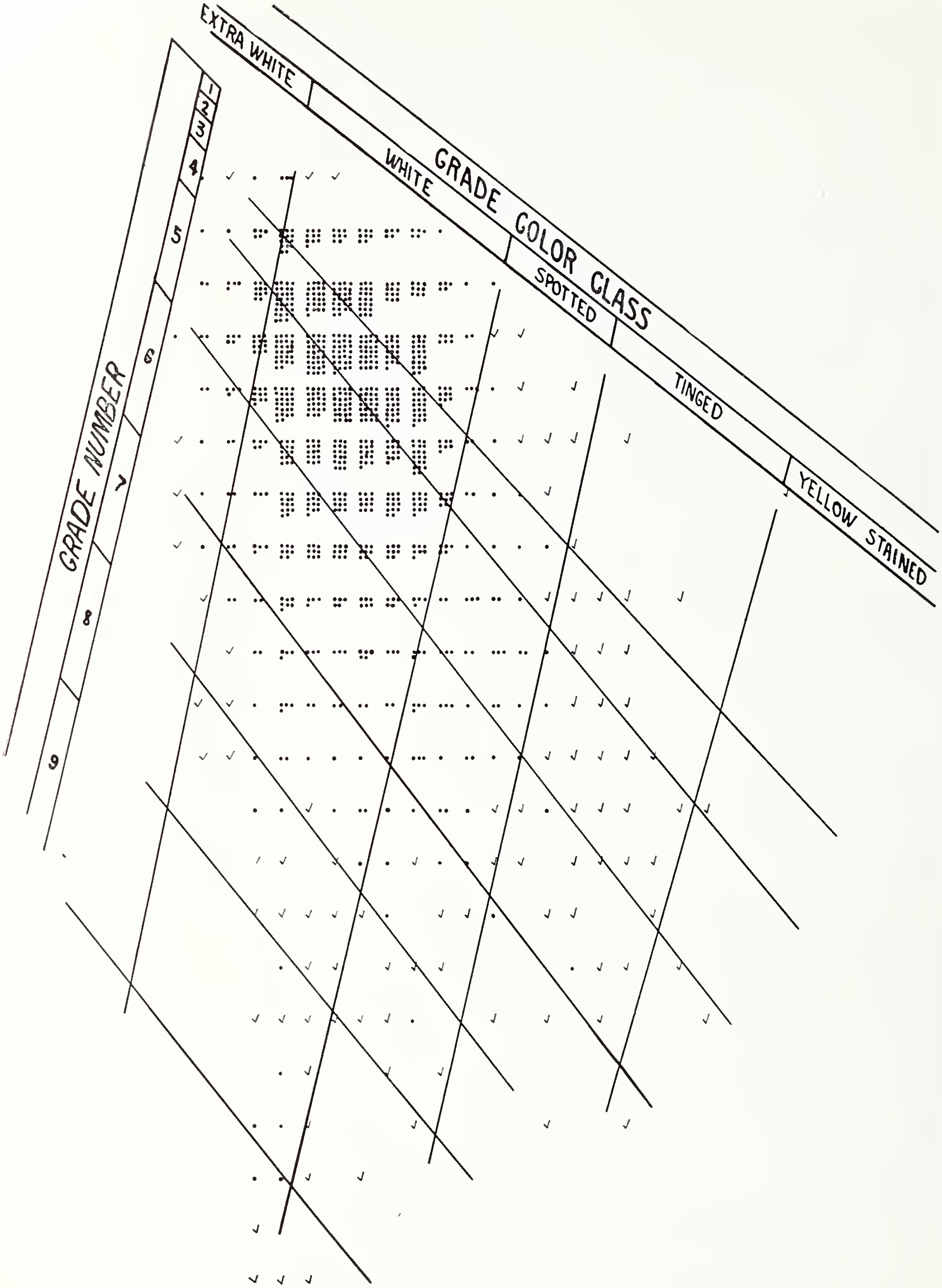

FIGURE 34.—A color plot of the 1936 cotton crop shown against a diagram representative of the color relations (value plotted vertically, chroma plotted horizontally) of the grade standards as changed in 1935, effective 1936. Each dot represents 0.1 percent of the samples measured; checks represent less than 0.1 percent. Shown against a diagram of the 1936 standards, crop surveys now indicate the bulk of the crop to be in the white grades, where they should be.

charts from color measurements, a large number of samples, representing the complete color range in each group or kind of hay, was collected and measured for color. Ten specialists in hay inspection then estimated the grade of each sample in terms of "percent natural green" and in terms that subdivided each grade into three units: High, average, and low for the grades—Extra Green; No. 1; No. 2; and No. 3—against which they were accustomed to grading.

Ideally, hay grades would be based on the direct measurement of factors representing feed value, but since no simple means of doing this is yet available the grades are based on factors which indicate their market value: Leafiness, color, and foreign material. The samples chosen for this study were free from wide variations in qualities of leafiness and foreign material, and were therefore typical of the various numerical grades.

For each grade, plots were made of hue against the average estimates of the inspectors, similar to the one for alfalfa hay shown in figure 35.

When color and grade run as close as in normal samples of alfalfa hay, it can be seen that development of a grade conversion chart, from which tables can be constructed to give the grade by reference to the color measurement, is a relatively simple matter.

For hay, use of the hue factor seems sufficient for grading work, but for cases in which all three attributes seem significantly related, a three-dimensional study can be made by use of a box, illustrated in figure 36, the top of which is punched with holes in regular formation. With this equipment the relations of the three color attributes in hay may be studied at the same time

FIGURE 36.—Illustration indicates how all three color factors related to grade can be studied by fitting graduated sticks into holes in the top of a box. Relative hue and chroma positions may be plotted by the position of the sticks on the board, and color value may be indicated by the length of the stick shown above the chart level. Pins of different colors may be placed in the top of the sticks to indicate duplication of readings.

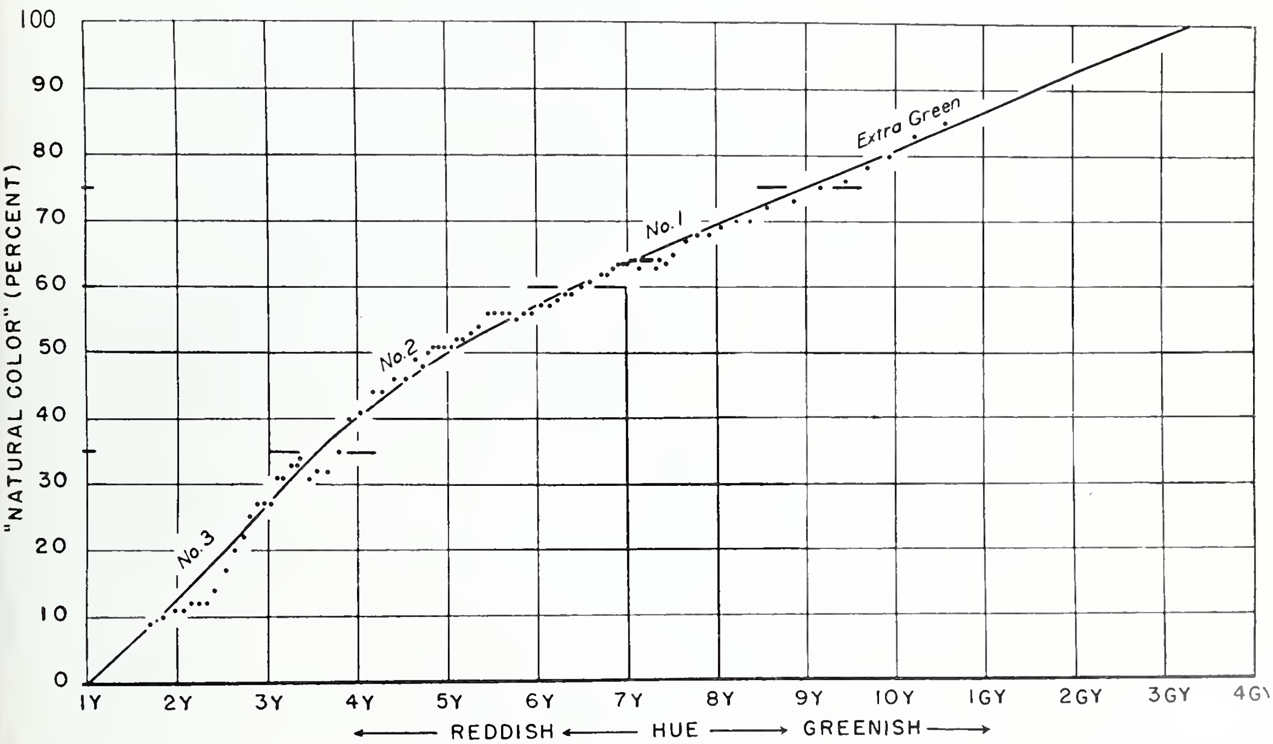

FIGURE 35.—Moving averages of estimates of alfalfa hay made by inspectors in terms of "percent natural green" against measurements of Munsell hue. Results show so definite a relation that a color conversion table for alfalfa hay can be based on hue measurements. Lines at 35 percent, 60 percent, and 75 percent natural color divide the samples into four grades: Extra Green for samples measuring greener than 9Y; Grade No. 1 for samples between 6.5Y and 9Y; Grade No. 2 for samples between 3.5Y and 6.5Y; and Grade No. 3 for samples redder than 3.5Y.

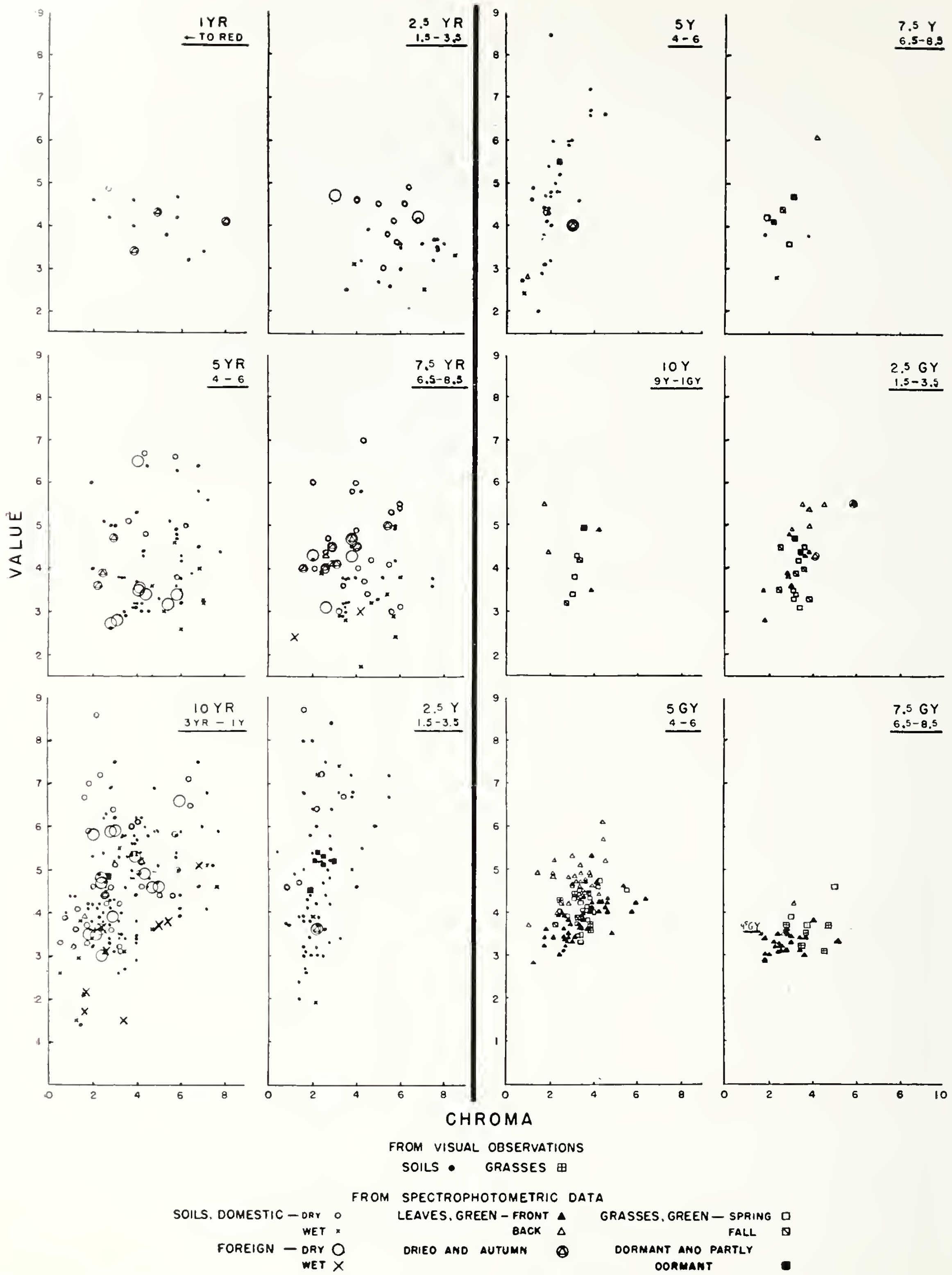

FIGURE 37.—Distribution of daylight color of typical samples of soils, foliage, and grasses plotted for value and chroma on a series of Munsell hue charts (from samples redder than 1YR, through charts spaced every 2.5 hue steps to 7.5GY). Such data provide the necessary basis for setting color standards for these objects.

by fitting graduated sticks into the holes and setting them lengthwise for hue, widthwise for chroma, and vertically for value. These sticks may be pushed down into the box until their length above the top represents the value of a particular sample. Balinkin (*6*) has used this method, with pins stuck into a board, the head of each pin representing a point in color space, to study the color variations in batches of tile intended to be the same color. Use of such a model enabled him to indicate lots that could be sold together within a consumer's color tolerance.

These examples of methods by which grading problems may be studied and color conversion tables prepared are given as an indication of the diversity of these methods. Statistical methods of multiple correlation have proved very useful and are recommended.

APPLICATIONS OF MUNSELL NOTATIONS IN RELATED PROBLEMS

Color problems are a part of many research problems. For example, we need to know: How much the grade of cotton changes with exposure in the field before picking;[29] how much cotton changes in color with storage;[30] what effect a few not completely ripe tomatoes will have on the canned product (*41*) ; the color of crust and crumb in bread (*26*) ; how to assure the best color in commercially baked cake (*24, 25*) ; the cause of dark color in potato chips (*70*) ; the relation of cold storage conditions to color in preserving cranberries; the relation between high temperature forewarming and the color and heat stability of evaporated milks (*7*) ; and the relation of wheat types to macaroni color.[31]

Perhaps a study of the color of soils and foliage is needed as a basis for camouflage of natural objects (*59*), or a method for specifying colors needed in color-blind tests (*13*) or color aptitude tests (*10, 11*). Applications such as these may be direct, as in the measurement of a carefully selected representative group of soil and foliage colors, illustrated in figures 37 and 38. In this case both daylight and photographic appearance were needed. Munsell notation was used for indicating the daylight color distribution of typical samples in figure 37, and spectrophotometric curves extended into the infrared (fig. 38) indicate their photographic qualities.

Other applications are not so direct. For example, the soil color measurements represented in figure 37 were originally obtained in order to establish a series of color standards and color names for soils (*65*). The problem of selecting and naming a series of 40 to 50

[29] Nickerson, D. Grade of cotton affected by exposure in the field. U. S. Dept. Agr. 12 pp. 1933. [Processed.]
[30] Nickerson, D. Color stability in raw cotton, II. Storage tests. U. S. Dept. Agr. 1941. [Processed.]
[31] Fifield, C. C., Clark, J. A., Hayes, J. F., and others. Milling and macaroni experiments with durum wheats, 1932-1936. U. S. Dept. Agr. 1937. [Processed.]

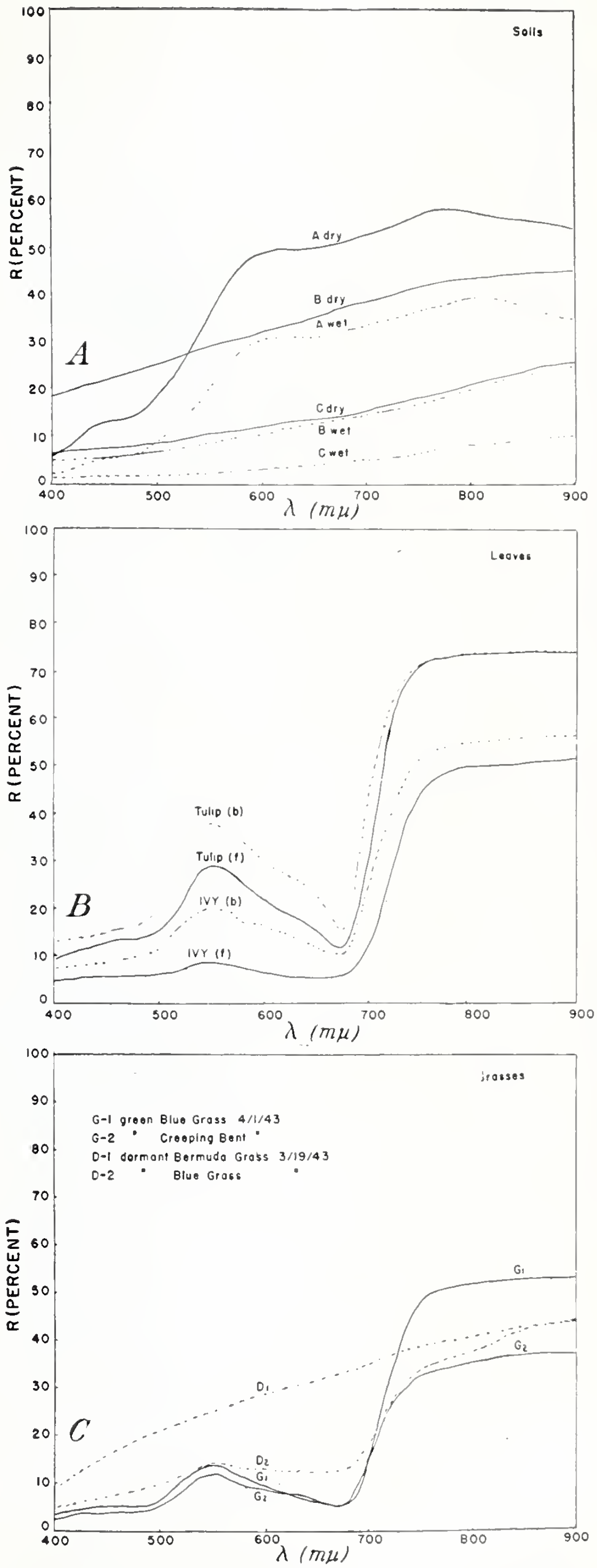

Figure 38.—Spectrophotometric curves shown for typical samples of soil (A), foliage (B), and grass (C) colors plotted in figure 37. Such additional information may be needed to indicate the photographic qualities of colors. Note that these curves extend through the visible spectrum (400 mμ to 700 mμ) out into the infrared as far as 900 mμ. Sometimes a knowledge of daylight color may not be sufficient to solve a color problem; it may need spectrophotometric data also.

colors to represent this color range would have been comparatively easy if soil scientists had not already been using some sort of color language. After several years were spent in getting a representative series of 250 soil colors, they were measured in Munsell notation. The next step was to discover what color names soil scientists gave to the colors of these samples. The average number of different name designations given to each of the 250 samples was over 12, which meant that no naming method would suit everyone. But a naming method based on the ISCC-NBS[32] (*38*) report was finally decided upon, names covering the soil color range were selected, and samples were made up to represent them, by reference to the Munsell color measurements. (This naming method is such an important one for standardization in grading work that it is described in a later section of this publication.)

By using numerical data for hue, value, and chroma it is possible to employ color as one of several factors in statistical studies of quality. For example, cotton spinning quality is made up of many factors, some of which are measurable, some not. Color has been added to the measurable factors, and together with fiber length, uniformity, and strength, has been used in statistical studies to discover the total and relative contributions of these various factors to the quality of yarn spun from measured cottons.

When the relation of color to other and harder-to-measure quality factors is high, color can be used in place of the more difficult measurements. For example, it is not because green color in hay is desirable to look at that the green grades rank high in the grading scale, but because the feed value of hay is so directly indicated by color. Chemical studies of vitamins and other nutritional elements and animal feeding tests are being conducted at various experiment stations. So far such studies indicate that, in general, high-grade or greener hays have better feeding value than other grades.

Experiments conducted by the United States Bureau of Dairy Industry show that when U. S. No. 1 Timothy was fed to dairy cows as their only source of carotene or provitamin A, the cows remained in good health and produced normally, but that when for a period of 6 months or more the ration consisted of U. S. No. 3 Timothy the cows usually dropped immature, weak, or dead calves. When milk from cows that received the U. S. No. 3 Timothy ration was fed to calves normal at birth, they died within 3 months. These same experiments showed that the color of butter varies definitely with the green color and carotene roughage fed to cows. For example, the color of butter from cows fed U. S. No. 1 Timothy as the sole roughage is a much deeper yellow than that from cows fed solely on U. S. No. 3 Timothy.[33]

Negative relations are as important to know as positive ones. Although the color of egg yolks is a direct result of the kind of feed given poultry, the color of shell is related to breed. Color often indicates when fruits are ripe, but color induced by artificial means is no indication of ripeness. Natural yellow color in butter, as of so-called June butter, indicates high natural vitamin content from pasture feeding; artificially colored products on the other hand give no indication of relative vitamin richness. Apples are often bought on their looks—by their color. But many an unsuspecting customer has bought the better looking of two apples only to find that color was no indication of eating quality—that variety is more important than color.

Color is a very important measure of the relative success of different methods of freezing and dehydrating foods, but there is still much work to be done in this field.

In many research studies in which color is only one of many factors, measurement seems too specialized—perhaps too time-consuming—to be undertaken by a laboratory worker untrained in color. For such cases the use of Munsell color charts with the mask method is advised. Results will be in terms of the Munsell notation and if, later on, disk colorimetry is used in the same laboratory the results should be comparable. Use of both methods in the same laboratory provides for quick chart comparison as well as the more accurate color comparison of carefully prepared samples by means of disk colorimetry.

When comparisons are to be made between results of these two methods, it is important to make sure that illuminating conditions are the same in both cases and that re-notations have been used for the Munsell chart colors. Even then there will be differences due to viewing methods, for in using an instrument the observer is often entirely or partially dark-adapted and in an instrument the comparison field is surrounded by black, and reaches the eye at a very small visual angle. In viewing charts it is usual for the observer to be light-adapted, to use a gray mask, or even to compare large samples. Restriction to a visual angle of only a few degrees is provided for in most colorimetric instruments in order that the comparison will be made at the fovea centralis—the central area of the eye—which is most sensitive to color and uniformly responsive. Brightness measurements may be made to the closest tolerance when using a photometric field in which the dividing line between sample and standard disappears. But while judgments of chromaticity differences can be made to a fairly small tolerance with samples the size of those on the Munsell charts, the tolerance can be made smaller by use of large areas with as little dividing line as possible between samples. Thus, differences in colors that may be close enough to be called a match by the mask method will be greatly magnified if a 2-inch square sample of one is placed on a 6-inch square of the other.

The method employed should depend on the use for which the results are intended. If a tolerance of matches made by the mask method is sufficient, the judgment of the observer should not be upset by placing large areas of one sample against another. On the other hand, if the final result is to be used in a comparison of one sample with another, the tolerance met by the mask

[32] Inter-Society Color Council—National Bureau of Standards.
[33] Annual Reports of the Chief of the Bureau of Dairy Industry, U. S. Dept. of Agr.: 1937, 19–20; 1938, 20–21; 1939, 27; 1940, 36–37; 1941, 34–46. For sale by the Superintendent of Documents, Washington, D. C., at 10 cents.

method would be too large. The effect would be similar to that obtained by using a ruler instead of micrometer calipers for measuring small and very accurate lengths.

THE KELLY MASK METHOD FOR COLOR MATCHING

Several years ago, Judd and Kelly (*38*) devised a mask for use in comparing the color of drugs and chemicals with color standards. This mask is now available[34] in gray, black, or white, for convenient use with the pocket edition Munsell charts. Such masks can be homemade (they should have attachments on the back to hold the charts in place while the sample is manipulated). Figures 32 and 39 show pictures of the mask with its

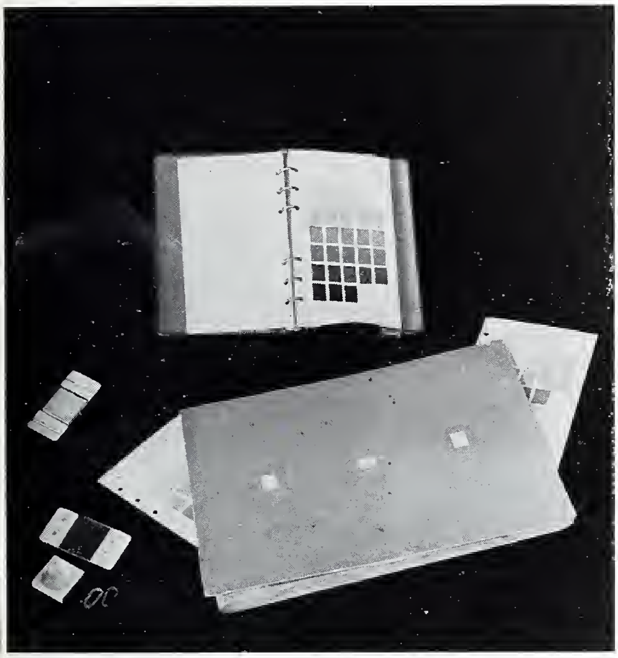

FIGURE 39.—Materials needed for use in Kelly mask method of matching the color of samples to the nearest Munsell color samples and interpolating the notation to the nearest 0.5 step of hue (out of 100), and the nearest 0.1 step of value and chroma. The mask has triple openings so that pocket-size charts of colors, between which the color of the sample falls, may be slipped in behind the outer openings, and the sample placed behind the center opening.

triple openings and the way in which the charts may be used—the sample being placed behind the center opening and samples on adjacent hue charts being moved into place behind the other two openings. Samples of powdered drugs may be placed in containers, as illustrated in figure 39 (see also fig. 32).

The illumination may be natural or artificial daylight. If natural daylight is used it is preferable to use light from a north window (because there is less color change in such light, throughout the day, than in light from any other exposure). A table may be placed at the window so that light from the unobstructed sky reaches the table at an approximate angle of 45°. A canopy of black cloth hung above or behind the sample so that it is imaged in the cover glass of the sample container will eliminate errors from admixture of undesired light reflected from surrounding surfaces. I. C. I. standard specifications for illumination and viewing call for 45° illumination and perpendicular viewing. These conditions may be reversed if an overhead skylight or an overhead artificial daylight unit is used. Illumination on sample and standard must be the same, otherwise different Munsell notations will be found by interchanging sample and standards. Even with good illumination it is good practice to check comparisons by an interchange of this sort.

First, a general comparison of the sample with the Munsell charts is made in order to select the two adjacent hue charts between which the color falls. These adjacent hue charts are then placed, one on each side of the mask (one chart is generally put in upside down because of space restrictions), the sample is held behind the center opening, and the charts are moved until chips of color nearest to that of the sample come into view in the other two mask openings. The nearest colors are not hard to find unless the color to be matched is outside the limits of the selected charts. If, for example, two soil samples are to be measured, one may look as if it belonged between the 10YR and 2.5Y charts and the other between 7.5YR and 10YR. In one case the sample may be a good match for the 10YR 5/4 chip. The other may fall between 3/ and 4/ value, /2 and /4 chroma, and 7.5YR and 10YR hue, the notation of the sample to be obtained by interpolation, for value first, then chroma, and finally hue. The value may seem about 3.6/, the chroma about /2.5, and the hue about 8YR which is one-fifth of the way from 7.5YR toward 10YR. The interpolated notation matched according to the color chips is 8YR 3.6/2.5. If re-notations according to the smoothed Munsell system are needed, comparison should be made in terms of re-notations for these color chips (*47*). The chips used in the above comparison are as follows:

Book notation	*Re-notation*	*Book notation*	*Re-notation*
7.5YR 4/4	7.5YR 4.2/4.5	10YR 4/4	10YR 4.2/4.6
7.5YR 4/2	8YR 4.1/2.3	10YR 4/2	9.5YR 4.2/2.4
7.5YR 3/2	7.5YR 3.2/2.6	10YR 3/2	10YR 3.2/2.5

Interpolations are usually made in terms of half hue steps and tenths of value and chroma steps. It is evident, therefore, that a book notation of 8YR 3.6/2.5, obtained by reference to the foregoing chips, will give, if greatest weight is assigned to the closest chips, a re-notation of 8YR 3.8/3.0. Weighting can generally be done by inspection. When the sample is less than 0.6 hue steps, 0.3 value steps, and/or 0.6 chroma steps from one or more of the surrounding chips, a simple rule to follow in setting the re-notation is to consider only the chips that are within these limits. Only when a sample is midway between chips and there is doubt as to which way the average goes, need all the surrounding chips be taken into consideration. Although a careful mathematical weighting of all surrounding chips could be made, the results thus obtained seldom would be worth the extra trouble, for usually they would be no more

[34] From the Munsell Color Co.

significant colorimetrically than those established after correction by inspection. If the re-notation is established at the time the color comparison is made, the relative weights that should be given each chip in arriving at the notation will be known; otherwise the above rule is a simple one to follow. When the result is on the half-way mark, as it is for hue in the above example (between 7.5YR and 8YR), then other surrounding hue re-notations may be used to decide whether the difference should be used as 0 or as 0.5. In this case the majority of hue re-notations are the same as the book notations; therefore a 0 correction is applied. If the majority were 0.5 steps, then an 0.5 correction would have been used. For value, using only the nearest samples (7.5YR 4/2 and 7.5YR 3/2), the correction averages $\frac{0.1 + 0.2}{2}$. Since this is 0.15, the other nearby re-notations are inspected to see whether the correction should be 0.1 or 0.2, and since most of them are $+ 0.2$, the value correction applied is $+ 0.2$. The chroma correction is $\frac{0.3 + 0.6}{2} = 0.45$, and since the majority of the other surrounding chroma differences are 0.5, the 0.45 chroma result is rounded off at 0.5, thus arriving at the complete re-notation given above.

On 250 soil samples two observers[35] made independent judgments by this method with an average difference in book notation of 0.6 ± 0.8 hue, 0.2 ± 0.2 value, and 0.3 ± 0.4 chroma. The averages are given with their standard deviations to indicate how close the results were. The hue differences might have been reduced further if hue charts had been used only 2.5 steps apart instead of 10 steps. For a large volume of work there is less changing of charts, and greater ease of decimal interpolation if charts used for comparison are 10 hue steps apart, as 5YR with 5Y, or 10YR with 10Y.

The mask method is a simple one to use, and after practice gives results that are much more satisfactory than an attempt to match colors on a chart without screening off equal areas for comparison and without using a constant background. Masks of neutral gray about value 5/ are best if all kinds of colors are to be compared, but a white mask should be used for light colors and black for very dark colors. The best mask to use is one close in value to the samples being measured; if all samples in a series are 3/, then use an N 3/ mask.

A thorough understanding of the hue, value, and chroma color solid is essential if this mask method of interpolation is to be used, for any degree of precision can be obtained quickly only by knowing what to look for. Such an understanding can be self-taught.

STANDARD NAMES FOR COLORS

There are times, such as mentioned in connection with the establishment of standard soil color names (*65*), when it is necessary or desirable to use standard color names in general color specifications; and in such cases use of ISCC-NBS color names (*38*) is recommended. Not only is it necessary to know that a particular soil color may be a weak reddish brown, but it may also be useful to know that Starlight Blue of the Standard Color Card of the United States Textile Color Card Association is a pale purplish blue, or that Laurel Oak in the Maerz and Paul Dictionary is a weak reddish brown. Use of standard color names, such as the list of color names for agricultural products given in the first few pages of this publication, could be used to help define commercial and trade names for colors.

The ISCC-NBS method was developed to answer the request[36] for a system of color designations that would be sufficiently standardized to be acceptable and usable by science; sufficiently broad to be appreciated and used by science, art, and industry; and sufficiently commonplace to be understood, at least in a general way, by the whole public. With the assistance of the American Pharmaceutical Association, plans worked out by the Inter-Society Color Council were developed at the National Bureau of Standards, and boundaries were set for the color designations recommended.

The ISCC-NBS method is simple in principle. The terms "light," "medium," and "dark" designate decreasing degrees of lightness, and the adverb "very" is added to extend the lightness scale to "very light" and "very dark." The adjectives "weak," "medium," "strong" and "vivid" designate increasing degrees of saturation. In order to avoid unwieldy and awkward adjective combinations, the words "pale," "brilliant," "moderate," "dusky," and "deep" are substituted for certain lightness and saturation combinations, as indicated in figure 40.

Pink, red, orange, brown, yellow, olive, green, blue, purple, and combinations formed by using two of these color names as blue-green or by using an "ish" suffix (as in purplish pink) cover the hue names; white, gray, and black cover the neutral series.

The relationship of these color designations to each other can best be understood by reference to the Munsell color solid (fig. 7). Each color designation of the ISCC-NBS method defines a block in the surface-color solid, and the complete system provides for 312 such blocks. This number is sufficient for naming colors from memory. However, since it is estimated that man can distinguish several million colors [2 million under good visual color-matching conditions, 8 million under the best instrumental conditions (*61*)], each block must necessarily contain a number of distinguishable colors. When more than the number of names provided by this system is necessary, the Munsell system of numerical notation is advised, for the reason that number relationships are remembered more easily than name relationships when the system must be extended to include a greater number. Figure 41 shows a portion of the color-solid with the name blocks indicated for the purples and neutrals.

It may be noted that certain of the hue names cover all lightnesses and chromas, as in the case of green, blue, and purple, but that others cover limited ranges, as the pinks, which are in reality light reds, and the olives, which are actually dark yellows. But usage is so strong

[35] K. L. Kelly and D. Nickerson.

[36] Made by the Color Committee of the 1930 United States Pharmacopoeial Revision Committee to the Inter-Society Color Council, and through it to the National Bureau of Standards.

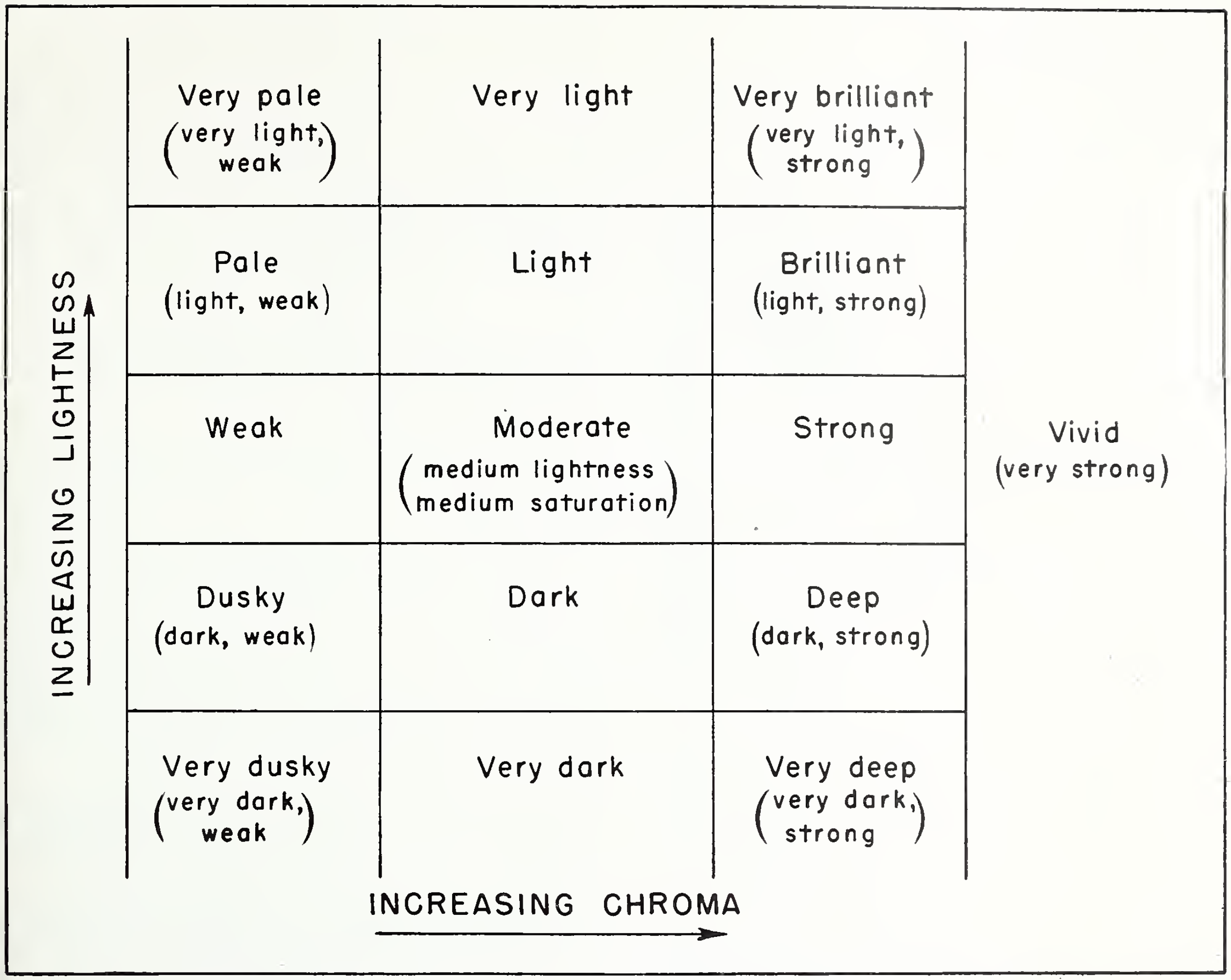

FIGURE 40.—Relation of adjective modifiers for the ISCC-NBS method of designating colors.

in regard to such terms that the ISCC-NBS method has taken them into consideration and applied different names to limited ranges of lightness and saturation in single hues. Brown is the name given to dark yellow-reds, orange to light and medium-to-strong chroma yellow-reds. Each such term is then divided into several color blocks by use of the modifiers listed in figure 40.

The most important part of the work done by Judd and Kelly (*38*) was the designation of boundaries for each color designation. Without boundaries the method would be of little practical use, but with the boundaries (even if one does not agree with them)[37] it is possible to specify a name and know that the color referred to comes within the boundaries set in the standard naming method. The boundaries are set in terms of the Munsell color chips, and they in turn have been measured in I. C. I. terms. Central notations have been published for each name (*60*). The Kelly mask method of color comparison already described was originally developed in order to obtain standard color names for the several thousand colors mentioned in the United States Pharmacopoeia and the National Formulary, used by every doctor and druggist in the country. The Munsell notation for the sample is obtained and the color name established by reference to 34 boundary charts in the Judd-Kelly report (*38*). Figure 42 illustrates one of the more complicated of these charts. Because abbreviations are often used in this method, a standard notation for recording them is given in table 4.

[37] Recommendations based on practical usage that can be made generally applicable (not just to a single science or industry but to all sciences or industries concerned with color) will be used as the basis for consideration of revisions.

TABLE 4.—*Abbreviations for use with ISCC-NBS system of designating colors*

Noun form of hue	Adjective form of hue	Modifiers
Pk: pink	pk: pinkish	lt: light.
R: red	r: reddish	dk: dark.
O: orange	o: orange	wk: weak.
Br: brown	br: brownish	str: strong.
Y: yellow	y: yellowish	med: medium.
Ol: olive	ol: olive	viv: vivid.
G: green	g: greenish	
B: blue	b: bluish	pale: pale.
P: purple	p: purplish	bril: brilliant.
Wh: white		mod: moderate.
Gr: gray		dusky: dusky.
Bk: black		deep: deep.
		v: very.

The best example in agricultural work of the need and use of such a standard-naming system as the ISCC-NBS has been its recommendation for use in the naming of soil colors in a publication of the United States Department of Agriculture, Preliminary Color Standards and Color Names for Soils (*65*).

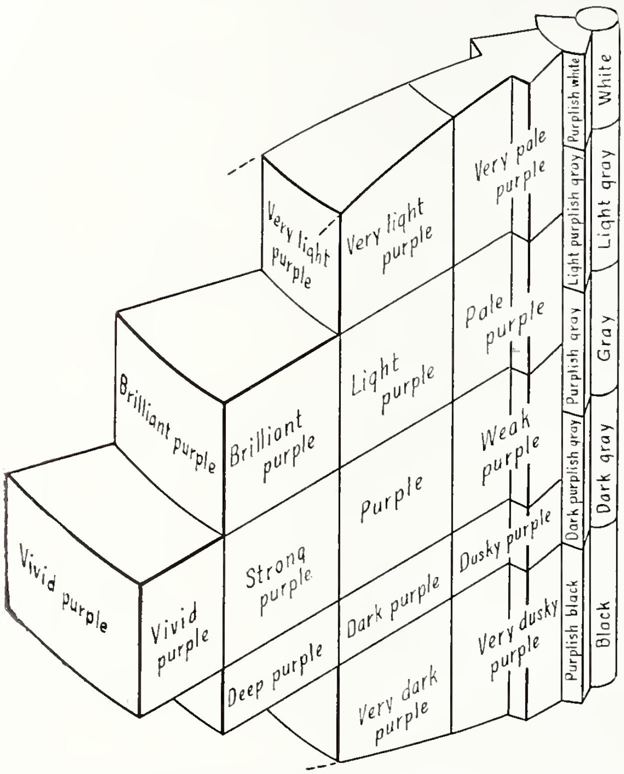

FIGURE 41.—Purple section of Munsell color solid here illustrated shows relation of ISCC-NBS system of color names. Color name blocks are illustrated for the purples and neutrals. All the colors that may be distinguished in any one of the name blocks are called by the same name.

A.S.A. STANDARD FOR THE SPECIFICATION AND DESCRIPTION OF COLOR

The year 1942, in which the American Standards Association adopted an American War Standard for the Specification and Description of Color, was an important date in colorimetry in this country. This standard draws together under a single heading the several related methods that are necessary in any basic understanding or application of colorimetric methods. The fact that the standard was requested by commercial and industrial groups indicates how far from the technical laboratory colorimetry has now gone in its applications. These commercial and industrial groups knew, as the foreword to the standard states, that use "of the Munsell Book of Color bridges the gap between the aesthetic and qualitative comprehension of color employed by artists, designers, and the general public, and the basic specifications employed by and necessary for the purposes of science and industry." And they were instrumental in seeing that an American standard was put on record that would show the relation of spectrophotometric, I. C. I., dominant wave length-purity, Munsell, and ISCC-NBS methods, all of which are related, and each of which fills a definite need in certain phases of colorimetric work. Because of its importance and its relation to the color work described in this publication, the text of the American War Standard for the Specification and Description of Color is given in full:

American War Standard
Specification and Description of Color

(ASA—Z44-1942)

1. PURPOSE

To recognize and recommend a basic method for the specification of color, and to facilitate its popular interpretation.

2. PROVISIONS

2.1* The spectrophotometer shall be recognized as the basic instrument in the fundamental standardization of color.[1]‡

NOTE: Specifications of the spatial distributions of the incident and collected light are essential to the standardization of spectrophotometry. Until standard conditions are established by agreement, the particular conditions employed in each instance should be stated clearly.

2.2* Color specifications computed from spectrophotometric data shall be found by means of the standard observer and coordinate system adopted in 1931 by the International Commission on Illumination.[2, 3, 4]

In the absence of a special reason for adopting some other illuminant in reducing spectrophotometric data, standard ICI illuminant C, representative of average daylight, shall be used.[2, 3, 4]

The basic specifications of color shall consist of the tristimulus value, Y, and the trichromatic coefficients, x and y, of the ICI coordinate system, or they shall consist of the tristimulus value, Y, and the dominant wavelength and purity.[3, 4]

NOTE: Dominant wavelength and purity are obtainable by computation [3, 4] from the trichromatic coefficients, x and y. Several methods of expressing purity have been proposed and used to some extent. In this standardization, purity refers to the quantity which is called excitation purity in discussions [4, 5, 6] of the several possible purity scales. For the sake of uniformity, the symbol, p, and expression in terms of per cent is recommended for purity. Likewise, when Y is specified in terms of reflection factor it should be expressed in per cent, symbol, R. It is customary to express dominant wavelength in millimicrons, $m\mu$, and this practice is recommended, together with the symbol, λ.

2.3* For the popular identification of color, material standards may be used. The only system of material standards that has been calibrated in terms of the basic specification is represented by the 1929 edition of the Munsell Book of Color.[7, 8] The use of this book is recommended wherever applicable to the specification of the color of surfaces. Approximate identifications of Munsell hue, value, and chroma may be secured by direct visual comparison with the samples in the 1929 Munsell Book of Color. When the most accurate visual comparisons are needed, the mask method[9] is recommended. Wherever more exact Munsell notations are desired, they shall be found from the basic specification, Y, x and y by interpolation among the smoothed curves[10, 11] for Munsell hue, value, and chroma.

‡ The single numbers in brackets throughout the text refer to "References" appended to this standard.

* The alternative, but coordinated systems of color specification described in 2.1, 2.2, and 2.3 are each adequate for specification of color tolerance in those cases for which each system is useful and convenient. As in all engineering specifications, the tolerances in different industries vary and depend upon the uses for which the products are intended. Color specifications according to 2.2 and 2.3 are, strictly speaking, appropriate only for products viewed by normal vision, but in the absence of agreement on standards for anomalous color vision or vision at low illuminations no more appropriate color specifications are available.

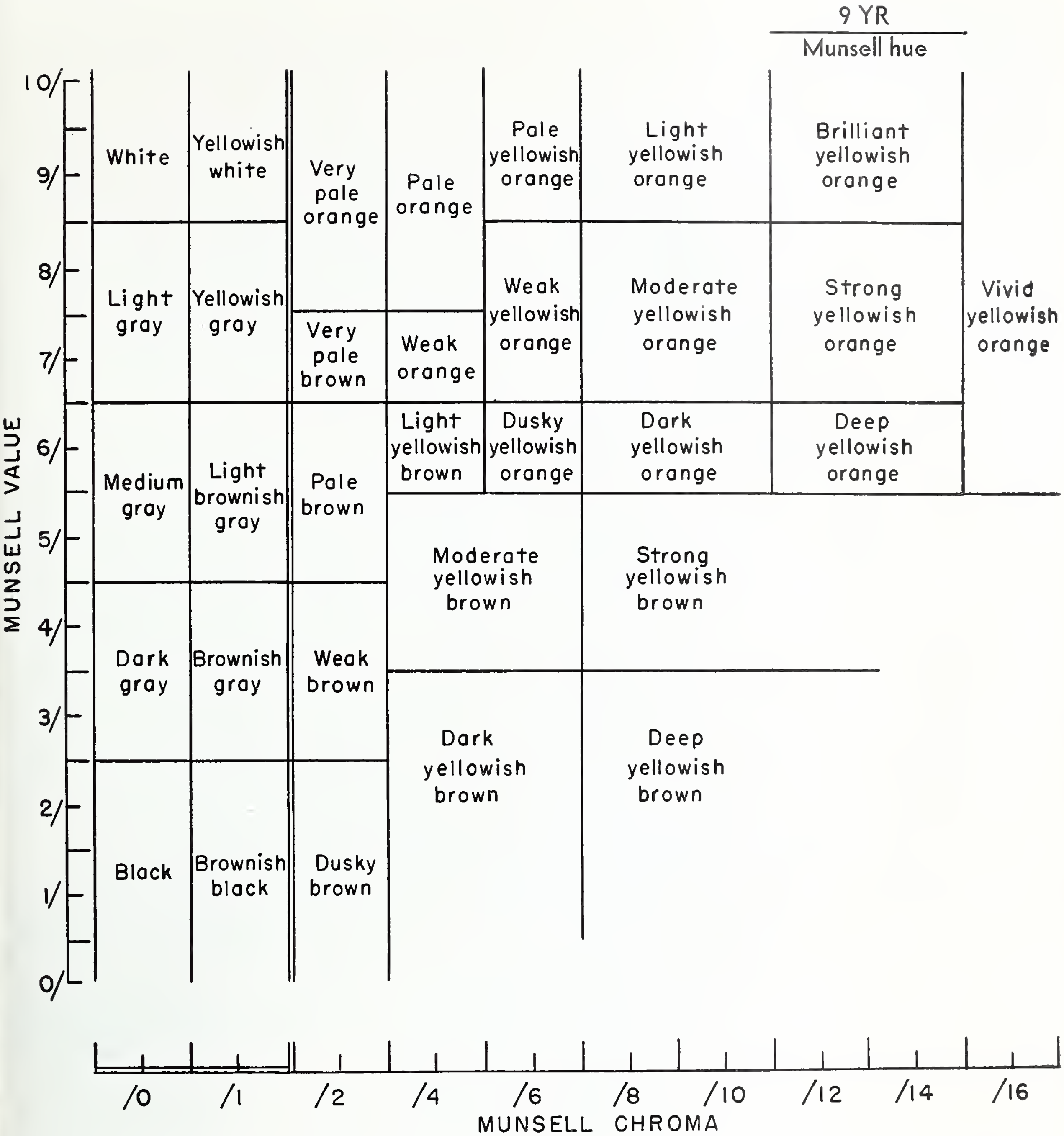

FIGURE 42.—Boundaries for each ISCC-NBS color name have been designated in terms of the Munsell colors and are published on diagrams similar to the one shown for colors that are 9YR in hue. This is one of the more complicated diagrams (the purple chart illustrated in figure 41 is simple by comparison), since it shows the hue name changes for different segments of the diagram including orange and yellowish-orange for the lighter colors, and brown and yellowish-brown for the darker colors.

NOTE: Most surfaces whose colors fall outside the range covered by the samples of the 1929 Munsell Book of Color cannot be assigned Munsell notations by reference to the smoothed curves. For such surfaces, for transparent media, and for illuminants, only the basic specification Y, x and y, or Y, dominant wavelength and purity are recommended.

2.4 A descriptive name according to the ISCC-NBS system of color designation[9, 12] may be derived from the Munsell notation. This name is recommended wherever general comprehensibility is desired and precision is not important. The use of color names for color specification is not recommended.

NOTE: It should be emphasized that the ISCC-NBS names are descriptive only and are not adapted to sales promotion nor intended to replace names that are developed for that purpose.

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[2] *Proceedings, Eighth Session, Commission Internationale de l'Eclairage*, Cambridge, England, September, 1931, pp. 19–29.
[3] D. B. Judd, "The 1931 I.C.I. Standard Observer and Co-ordinate System for Colorimetry," *Journal of the Optical Society of America*, Vol. 23, pp. 359–374 (1933).

[4] A. C. Hardy, *Handbook of Colorimetry,* Technology Press, Cambridge, Mass. (1936).
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[8] J. J. Glenn and J. T. Killian, "Trichromatic Analysis of the Munsell Book of Color," *Journal of the Optical Society of America,* Vol. 30, pp. 609–616 (1940).
[9] D. B. Judd and K. L. Kelly, "Method of Designating Color," *National Bureau of Standards Journal of Research,* Vol. 23, pp. 355–385 (1939); RP 1239.
[10] D. Nickerson, "Use of the I.C.I. Tristimulus Values in Disk Colorimetry," U. S. Department of Agriculture (May, 1938); mimeograph copies obtainable on request.
[11] S. M. Newhall, "Preliminary Report of the O.S.A. Subcommittee on the Spacing of the Munsell Colors," *Journal of the Optical Society of America,* Vol. 30, pp. 617–645 (1940).
[12] D. Nickerson and S. M. Newhall, "Central Notations for ISCC-NBS Color Names," *Journal of the Optical Society of America,* Vol. 31, pp. 587–591 (1941).

It should be pointed out that this standard was adopted in 1942 before publication of the final report of the O. S. A. subcommittee (*47*), which contains smoothed curves that supplant the preliminary curves contained in reference 10 of the A. S. A. Standard, and outdate the note in 2.3.

COLOR-TOLERANCE SPECIFICATIONS

A satisfactory method of expressing small color differences in terms of a single number instead of in three numbers (as for hue, value, and chroma) is useful in many cases, and is becoming increasingly important as rapid colorimetric methods are developed. To express the amount of fading, Nickerson (*52*) in 1936 based a small-color-difference formula on Munsell scales of hue, value, and chroma; Judd (*36*) in 1939 based one on his uniform chromaticity diagram; Scofield (*67*) has modified the Judd formula; and more recently formulas based on Adams' equations (*57, 1*) have been developed. In fact, a formula for the expression of small color differences in a single number may be made through use of any system in which the scales are regularly and closely related to perceptually equal steps.

In 1944, a symposium on Small-Color Differences was held at a meeting of the Inter-Society Color Council, co-sponsored by the American Association of Textile Chemists and Colorists and the Federation of Paint and Varnish Production Clubs, a full report being published in the May-July numbers of the American Dyestuff Reporter (*31*). Two papers published in 1944 (*58, 62*) cover the work done in this field to the present time. Table 5 (*58*) indicates the type of formulas available. An extended bibliography is given and a detailed comparison has been made (*62*) of several formulas applied to samples representative of nine series of camouflage colors for which an expression of color tolerance was desired.

Comparative results from this study, based on the same nine series of samples, indicate (table 6) that the Nickerson formulas (table 5) give results that correlate closer to average observations by a few percent over results for the other formulas. The Judd and Adams formulas (table 5) give results that average about the same, although those by the Judd formula would equal those by the Nickerson formula if it were not for a break-down in series No. 8. The Nickerson formula "I" is easy and quick to apply, the Adams formula $\Delta E_{A'}$, is also easy and quick to apply; the Judd formula ΔE_J requires considerable time. The formula that should be selected to give the most efficient results in time and accuracy depends upon the form of the color data available. But it should be remembered that results obtained by the use of any of these formulas can be repeated between laboratories only to the degree that measure-

TABLE 5.—*Small color difference formulas for use in expressing color tolerances, color fading, etc.*

Author	Symbol and formula	Type of color space on which formula is based
Nickerson	$I = \frac{C}{5}(2\Delta H) + 6\Delta V + 3\Delta C$	Munsell 3-dimensional concept of hue, value, and chroma (H-V/C)
Nickerson-Balinkin	$I' = [(\frac{C}{5} 2\Delta H)^2 + (6\Delta V)^2 + (20/\pi \Delta C)^2]^{1/2}$	Do.
Judd	$\Delta E_J = f_0 ([7Y^{1/4}[(\Delta\alpha)^2 + (\Delta\beta)^2]^{1/2}.10^2]^2 + [k\Delta(Y^{1/3})]^2)^{1/2}$ when $\alpha = \frac{2.4266x - 1.3631y - 0.3214}{1.0000x + 2.2633y + 1.1054}$ $\beta = \frac{0.5710x + 1.2447y - 0.5708}{1.0000x + 2.2633y + 1.1054}$ f_0 = 1.0 for matte surfaces $k = 100$	3-dimensional concept combining Judd UCS diagram with a scale of lightness, ($L = Y^{1/2}$)
Judd-Hunter-Scofield	$\Delta E_{H-S} = \sqrt{(L_1 - L_0)^2 + (a_1 - a_0)^2 + (b_1 - b_0)^2}$ when $L = 100\sqrt{Y}$ $a = 7L\alpha$ $b = 7L\beta$ and α and β are the same as in the Judd formula	Do.
Adams "Chromatic Value"	$\Delta E_A' = [(k\Delta V)^2 + [\Delta(V_X - V_Y]^2 + [0.4\Delta(V_Z - V_Y)]^2]^{1/2}$ when $k = 0.23$	3-dimensional concept in which the coordinates are V_Y, $(V_X - V_Y)$ and $(V_Z - V_Y)$, V being Munsell value
Adams "Chromatic Valence"	$\Delta E_A'' = [(k\Delta V)^2 + \Delta(W_X)^2 + (0.4\Delta W_Z)^2]^{1/2}$ when $W_X = [(X_c/Y - 1)]V$ $W_Z = [(Z_c/Y - 1)]V$ $k = 0.5$	3-dimensional concept defined by V_Y, $[(X_c/Y - 1)]V$, and $[Z_c/Y - 1]V$; V again being Munsell value, and X,Y,Z the I.C.I.tristimulus values for "C" illuminant

TABLE 6.—*Comparative results of several small-difference formulas. Correlation [using coefficient of multiple determination, R^2, as a measure (12)] of tolerance indices by 6 formulas against average visual placement of samples by 10 observers*

Color series No.	By formula—					
	Nickerson		Judd		Adams	
	I	I'	ΔE_J	ΔE_{H-S}	$\Delta E_{A'}$	$\Delta E_{A''}$
1	0.49	0.42	0.43	0.40	0.37	0.39
2	.42	.53	.55	.52	.53	.62
3	.58	.51	.67	.53	.65	.55
4	.78	.79	.77	.61	.71	.57
5	.48	.33	.40	.58	.50	.57
6	.86	.75	.48	.87	.75	.64
7	.90	.90	.92	.87	.86	.84
8	.35	.45	.00	.20	.21	.14
9	.53	.71	.58	.32	.21	.36
Average	.60	.60	.53	.53	.54	.52

ments of identical samples can be made and calculated to give identical results.

A typical application of formula "I" (originally called Index of Fading) of table 5 to agricultural work has been in the year-to-year study by Fifield[38] of the color change in Durum wheats grown in North Dakota.

It should also be kept in mind, as cautioned in 1936 [(*52*, footnote p. 512)] that while the layman and the commercial and the industrial man always asks for results in a single figure because he thinks it "easier to understand," he will probably know enough more about color when it becomes practicable to give him this one number, to realize that for most problems he needs to know the separate hue, value, and chroma differences that make up this total color-difference number. For example, the difficulties involved in adjusting a hue difference in textile-color matching may be much less than those involved in making a chroma match, or even a lightness match, and the dyer needs to know, not only the total color difference but also the color difference of the separate visual color attributes. Therefore, although a single number may be required to satisfy the request for "how much" change there is in a color as a result of fading, or "how much" departure there has been from a given standard, a great deal more can usually be learned when the color difference is expressed in three numbers instead of one.

ARTIFICIAL DAYLIGHTING FOR GRADING WORK

It is important in color grading of most agricultural products to have satisfactory natural daylight illumination; as most inspectors and graders know, a grade determined in an east window may vary a great deal from a grade determined in a west window, depending on the variations in daylight illumination on sunny days.

Good lighting is so important for cotton classification that the cotton industry goes to great lengths to provide it in classification rooms. What is known as a Government-type skylight was developed for cotton-classing rooms of the United States Department of Agriculture as long ago as 1914, in connection with services rendered under the Cotton Futures Act, and since then under the Cotton Standards Act.

Figure 43 shows a lighting system of the latest type—a skylight 80 feet long, set facing due north, with glass set at an angle of 72°[39] from the horizontal, a concave reflecting surface (following the arc of a circle) set opposite the skylight windows to diffuse the light, and no cross beams in the construction to throw shadows. Such rooms are painted a neutral gray (in a few cases with a black dado, white upper walls, and ceiling) so that no one chromatic color will be flattered or discounted more than another. The reflectance of the gray, or the use of black and white, should depend on the amount of light coming into the room and reaching the classing surface. If there is a great deal of light, as from an 80-foot skylight, the gray can be as dark as Munsell N 6/. If the skylight, or window space in a nonskylighted room, is small then N 7/ or even N 8/ is preferred because it allows the walls to reflect more light. A wall of N 6/ reflects only 30 percent of the light that falls on it; N 7/ reflects 43 percent; and N 8/, which is near to white, about 60 percent. The darker the gray walls, the more the light coming into the room will be absorbed by the walls. Use of white upper walls and ceiling allows reflection from above, and a black dado allows absorption by black walls below eye level.

Daylighting of classing rooms has been successful but not many classing rooms can be placed on the top floor, or in such a direction that a north skylight is feasible. The light from a north window that has proved satisfactory over a period of years may be shut off by the erection of new buildings or its color may be changed by reflection from brick walls. Weather may be bad during the peak of the classing season, or extra work may pile up that cannot be completed in daylight hours. When it became necessary for one of the field offices of the United States Department of Agriculture to move out of otherwise satisfactory quarters because a new building shut off the light, the business office in charge of space arrangements asked that a study be made to see whether it might be possible to prepare specifications for artificial daylighting that would be satisfactory for use when good natural daylighting is not available for the grading of farm products in which color is a factor.

A small unit of satisfactory artificial daylighting would have been sufficient in this case to avoid moving costs and a higher rental, but no one knew precisely what specifications would be necessary, or whether they could be met if they were available. It therefore became necessary to make systematic studies upon which such specifications might be based. Norman Macbeth, Sr., (*40*, *16*) had made a life study of artificial daylighting, but unfortunately his death occurred just as these studies began in 1936. However, as a result of contacts previously made with him, and through the cooperation of the National Bureau of Standards and technical workers in laboratories of several commercial lamp manufacturers

[38] See footnote 31, p. 45.

[39] Required by the latitude of Washington, D. C.

interested in the subject, studies were made in this field (*53, 54, 56*).[40] These studies are here summarized.

Most of the early studies were made with cotton but it was felt then, as now, that these studies would provide basic answers not only for cotton but for the color grading of other agricultural products graded in daylight, preferably in daylight from a north sky.

Experience in cotton work indicated that the light should be well diffused over a large enough area to permit the sample to be moved about freely, and that the light should be similar in color to light from a north sky on a moderately overcast day. These specifications are necessary because classifications made under artificial light should agree with classifications made under preferred conditions of natural daylighting.

Data on different amounts of illumination in various classing rooms were gathered hourly for 30-day periods during June and December with the results shown in table 7. Individual measurements varied widely, from 9:00 a.m. to 4 p.m.; they often varied by several hundred percent at a single position. For the average of maximum and minimum conditions called "Good," see table 8.

[40] NICKERSON, D. COMPUTATIONAL TABLES FOR USE IN STUDIES OF ARTIFICIAL DAYLIGHTING. U. S. Dept. Agr. 31 pp. 1940. [Processed.]

TABLE 7.—*Average of maximum and minimum illumination in foot-candles read hourly for 30-day periods in June and December, using a Weston Photocell meter for certain sky and classing conditions (for horizontal plane)*

Classing conditions	Sky conditions					
	Clear		Slightly cloudy		Overcast	
	June	Dec.	June	Dec.	June	Dec.
Very good	108–150	41–50	126–155	52–65	100–150	115–150
Good	118–145	51–60	147–174	64–77	204–252	106–122
Fair	109–149	37–48	138–158	65–75	137–160	80–91
Poor	119–148	31–36	140–168	65–74	99–118	61–70

FIGURE 43.—One of the latest type of skylights developed for cotton classing rooms of the United States Department of Agriculture. The skylight in this room is 80 feet long, set facing north, with glass set at an angle of 72° from the horizontal (related to the latitude in which it is built), a concave reflecting surface opposite the skylight windows to diffuse the light, and no cross beams in the construction to throw shadows.

TABLE 8.—*Average of maximum and minimum illumination in foot-candles for classing conditions designated as "Good" in table 7*

Classing room (location)	Weather conditions					
	Clear		Slightly cloudy		Overcast	
	June	Dec.	June	Dec.	June	Dec.
Washington (new bldg.)	180–190	34–45	220–235	45–55	220–250	--------
Washington (old bldg.)	120–140	40–50	200–230	65–75	250–275	55–65
Austin	120–150	80–90	130–160	150–160	270–310	175–190
Memphis [1]	85–100	55–60	110–120	50–60	--------	--------
Memphis [2]	140–240	80–105	220–295	70–100	200–250	--------
Houston	130–140	50–60	140–150	75–85	150–160	--------
Charleston	130–150	45–55	110–115	50–60	250–350	140–150
Atlanta	60–70	75	130–140	60–75	--------	90
Savannah	130–150	--------	140–150	60–70	--------	--------
New Orleans	70–90	12–13	80–110	14–19	90–125	--------
Dallas	180–220	30–40	150–185	55–70	--------	--------
Stoneville	70–100	54–60	140–200	75–90	200–300	120–125
Average	118–145	51–61	147–174	64–77	204–252	116–122

[1] Office of the Board of Supervising Cotton Examiners.
[2] Local classing office.

It is evident (table 7) that amount of light is not the only factor in determining whether color-classing conditions are good or poor. Only for overcast sky conditions in December are the average foot-candle readings highest for very good classing conditions and lowest for poor classing conditions. For clear and slightly cloudy conditions in both June and December and even for overcast days for June, the highest foot-candle averages are not selected as the best classing conditions. While amount of illumination was the only factor measured instrumentally, choice of classing conditions indicates that quality of light may be even more important than amount of light once a minimum amount has been reached. At the time when these studies were made there was no simple, accurate method of measuring the quality of natural illumination. A blue-wedge photometer developed by Priest at the National Bureau of Standards is a suitable instrument and was borrowed for this work, but calibration and operation of the instrument proved so time-consuming that quality measurements were omitted from these first tests. Since then further work has been done (an Inter-Society Color Council committee has adapted an Ansco-Sweet Densitometer to read approximate color temperature), but nothing is yet published. However, since it is quite generally known that color matchers in general—cotton classers included—prefer light from an overcast or "covered" north sky, it therefore seems probable that the data shown in table 7 are the result of averaging whatever amounts of illumination happened to be associated with the best liked quality of illumination (the most favorable energy distribution). In fact, light from a clear blue sky was generally called *glaring,* yet, as may be seen from tables 7 and 8, the amount of illumination on clear days is below that of slightly cloudy or overcast days. From this it seems obvious that high color temperature should be avoided. The following tentative specifications were therefore developed for artificial daylight: (1) Diffuse reflection over a relatively wide area (from a wide-angle source); (2) color (and energy distribution) to match that of a moderately overcast north sky; (3) 50-foot-candle illumination on a horizontal plane a minimum, 60 to 80-foot-candles satisfactory, with little advantage in amounts above 100 foot-candles (except perhaps for the inspection of black or other very dark colors).

It was expected that there would be difficulty in meeting specifications; therefore, the requirements for the first experimental set-up were as liberal as possible—at least 30- to 50-foot-candle illumination on the classing tables, a color temperature and relative energy close to I. C. I. illuminant C (tolerance limits 6,300° K to 7,000° K and for the filters a ratio of transmission at wave length 610 mμ to that of 700 mμ at least 0.9). The lamps were to be set behind a diffusing screen, to give the effect of skylight, and the diffusing glass requirements stipulated that when clear the glass shall transmit at least 91 percent of each wave length in the visible spectrum to be delivered sanded or etched on one side. Provision was made for forced draft ventilation.

The first experimental installation, illustrated in figure 44, used 15 1,000-watt lamps, with Corning Daylite filters (Macbeth 2AC L9) 5.5 mm. thick. The lamps were set approximately 24 inches between centers, three rows of five lamps each, and the filters 20 inches above

FIGURE 44.—Artificial daylight installation used in experiments to determine specifications necessary for satisfactory artificial daylighting for cotton and other agricultural commodity grading: *A,* Light in use; *B,* lamps provided with filters of Corning daylight glass, and construction of the diffusing glass panel that produces a skylight effect.

the diffusing glass which was set 8 feet from the floor. The result gave an average illumination on the table of about 100 foot-candles; with 500-watt lamps it gave about 50 foot-candles. The walls were a neutral gray, about N 7/.

The color of the illumination was well up to that of illuminant C, adopted by the I. C. I. to represent average daylight. Although the cotton classers pronounced the illumination "satisfactory" and thought that work might be done under it after a classer became accustomed to the light, they did not wholeheartedly approve it as a substitute for the overcast type of north sky they prefer to use. This point is important, for there is a psychological as well as a physical standard to be maintained. If the light is only "satisfactory" instead of really "good," then artificial daylighting will be used only when conditions make it absolutely necessary. If artificial daylighting is right, it will, in cases of conflict, be preferred to natural daylighting because of its constancy. Actually the cottons looked "too yellow" under illuminant C, not only to the cotton men but to any color-trained person. So the filter was changed to another melt of Corning No. 590 (Macbeth BDK 11) which, when used with lamps operated at 3,000° K gave a calculated color temperature of about 7,500° K. After examination of cotton standards under this light, it was accepted by the Cotton Appeal Board as providing light sufficiently like that from the overcast north sky which they prefer to make the cotton look natural. Since that time units of six 1,000-watt lamps, self-contained with filters and ventilating system to meet the specifications indicated above but at a color temperature of approximately 7,500° K have been developed commercially for installation over cotton-classing tables. These units are large enough that several of them can be installed end to end to provide a skylight effect.

Specifications now stipulate that

The lamps shall be large enough to supply an illumination of 60 to 80 foot-candles on the classing surface. Over the lamps glass filters shall be used. The filters shall be equivalent to or better than Corning Daylite (No. 590) with a spectral transmission curve such that the lamp-and-filter combination will give close to 7,400° K to 7,500° K in color temperature, with a relative energy curve that is a satisfactory match for daylight. The tolerance limits are 7,200° K to 7,600° K in color temperature and the ratio of the transmission of each filter at wave length 670 mμ to that of wave length 700 mμ must be at least 0.9 or more. The diffusing glass used in the unit shall be approximately nonselective, equal to or better than Crystalex plate glass, treated to withstand heat up to 650° F., and sanded or etched on one side.

In color matching and discrimination any study of the part that the illuminant plays may be divided into two broad sections. In one, the chief concern is to find an illuminant under which color differences, if they exist, can be seen. If an illuminant makes these differences easy to see, even though the illuminant be colored or peculiar in its characteristics, and entirely changes the daylight color of the paired samples, it may be satisfactory. The single illuminant most satisfactory for each pair of such samples will depend on the spectrophotometric characteristics of the samples. As reported by Taylor (*71*), the illuminant best adapted to this purpose is one rich in energy in the region of minimum reflectance of the samples in question. For examining yellows, an illuminant rich in the blue portion of the spectrum (where generally there are the widest spectrophotometric differences in yellow samples) will enable an observer to discriminate yellows better than under a yellow illuminant. When blue samples are to be examined, an illuminant rich in energy in the yellow and red portion of the spectrum will be the best choice.

The second broad section of study concerns the choice of an illuminant under which colors may be graded or selected in the same relation in which they would be graded or selected under an illuminant to which the observer had previously become accustomed—usually daylight. Artificial daylight therefore is of concern in grading work, although even in this work there are times when it would be desirable to have special lamps under which differences might be seen even if the "daylight colors" of the samples should turn into peculiar "lamplight colors."

A practical example of an application of the two methods is its use in combination "color-matching lamps" in dye houses. When samples are to be matched under such a lamp they are viewed first under one illuminant, then under another, the change being made by a foot switch so that while the sample need not be moved, the illumination can be changed from one extreme color of daylight—about horizon sunlight, perhaps near 2,300° K—to a color temperature of daylight at 6,500° K or above. The following specification for standard illuminants to be used in textile color-matching work is based on this principle. Selection of 6,500° K to 7,500° K in an energy distribution similar to daylight as the upper limit, satisfies not only the requirement for two widely different colors of the lamp but also the requirement for a satisfactory daylight color inspection. The standard specification explains so many points that it is given in full as adopted by the American Association of Textile Chemists and Colorists:

(AATCC) Tentative Specification for Standard Illuminants in Textile Color Matching (Revised June 26, 1942).[41]

Scope. 1. This specification applies to artificial illuminants which are capable of furnishing standardized light sources for judging the color of textiles.

Selection of Illuminants. 2. It is recognized that the colors of textiles in ordinary use may be observed in daylight under widely different conditions. Daylight color ranges from the reddish color of horizon sunlight at a color temperature of about 2,300° K, through noon sunlight at about 4,800° K, to average daylight at 6,700° K to 7,500° K, and from there to blue sky, which may range in color temperature anywhere from 10,000° K to 25,000° K or higher. If textile colors match under lamps representing two widely different phases of daylight it may be assumed that they will usually be a match under other daylight conditions. Two types of artificial illumination are therefore considered sufficient to satisfy the purposes of this specification—one illuminant to be representative of the lower range of color temperature, and the other to be representative of a range that represents preferred conditions for daylight inspection.

Specification of Illuminants. 3. The artificial light units shall be capable of supplying diffused illumination uniformly over an area large enough that the textile specimens whose colors are to be matched or graded may be moved about freely. The angular field subtended by the source of light at the sample shall not be small. The illumination on the working plane shall be 60 to 80 foot-candles for grading white and light materials (daylight

[41] Published in the Amer. Dyestuff Rptr. 31 (15): P363–P364. 1942.

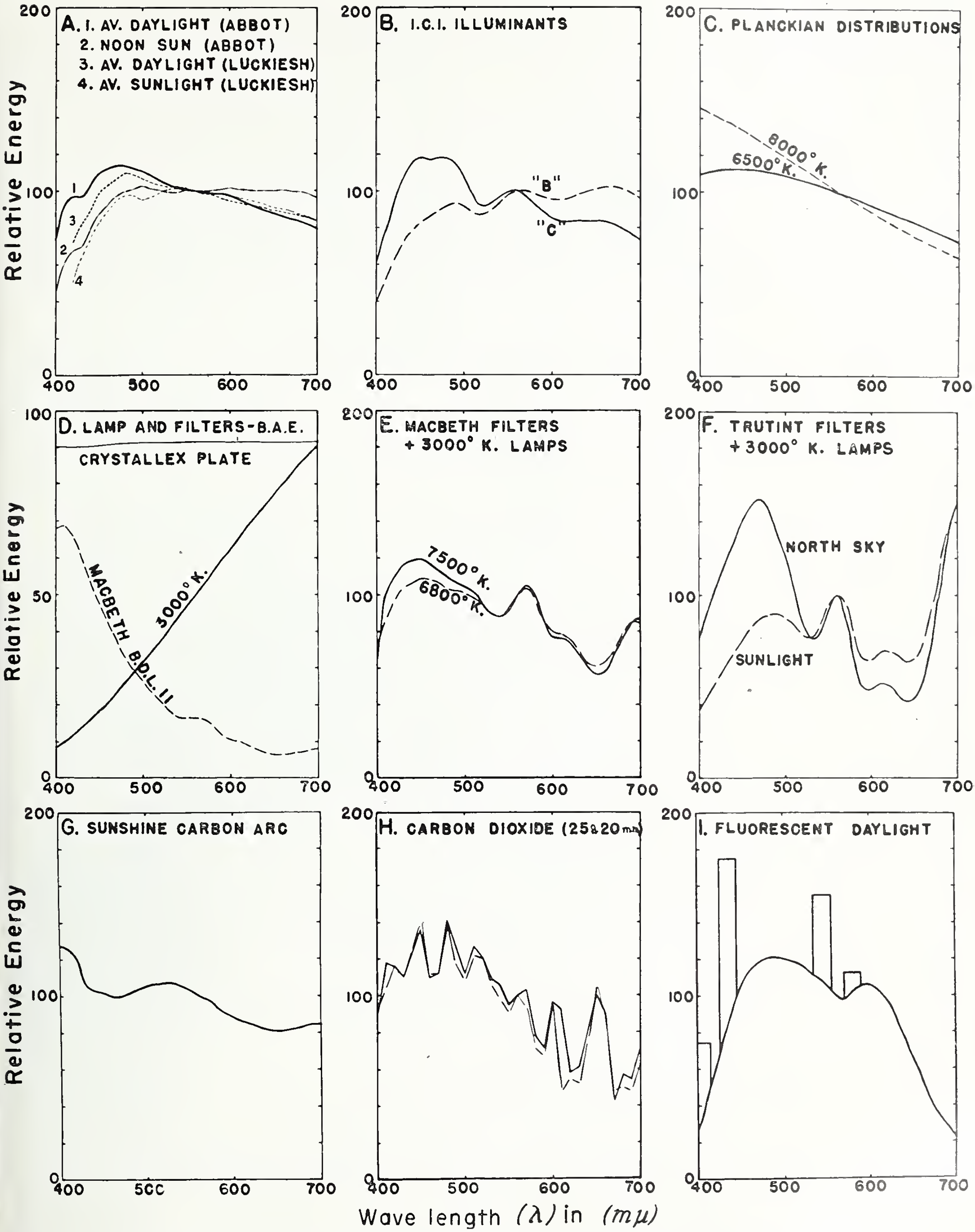

FIGURE 45.—Relative spectral energy distribution, reduced to 100 at 560 mμ, for a number of actual and theoretical illuminants considered before selecting a filter-incandescent lamp as the most satisfactory available substitute for daylight in color grading.

reflectance greater than 40 percent, or samples lighter than Munsell 7/); the illumination shall exceed 100 foot-candles for materials of intermediate lightness (daylight reflectance between 6 and 40 percent, or samples between Munsell 3/ and 7/); and the illumination shall exceed 150 foot-candles for dark materials (daylight reflectance less than 6 percent, or samples darker than Munsell 3/).

4. One illuminant shall be in general comparable to I.C.I. (International Commission on Illumination) Illuminant A, which is a tungsten lamp operated at 2,848° K. But since horizon sunlight at 2,300° K is also in the low range of color temperature yet is enough redder so that it is preferred by many for textile color matching, the tolerance allowed for the illuminant to represent the low range of color temperature is 2,300° K to 2,900° K in order to provide a wide latitude that will include the use of either. For check comparisons between laboratories the tolerance shall be limited to ± 25° K.

5. One illuminant shall be in general comparable to I.C.I. Illuminant C, a tungsten lamp operated at 2,848° K with a specially prepared liquid filter that raises the color temperature to about 6,700° K, and gives a color which approximates that of average daylight. But since this standard is lower in color temperature than is preferred in most daylight inspection work, and since there is very general agreement that 7,500° K comes nearer to the preferred illuminant (moderately overcast sky from the north), the tolerance allowed for this illuminant is 6,500° K to 7,500° K. For check comparisons between laboratories, the tolerance shall be limited to ± 100° K. This specification can be satisfied by a tungsten filament lamp of suitable wattage, plus a glass filter equal to or better than Corning No. 590, the filter to be of a thickness that will give the required color temperature. The energy curve of the illuminant, if it differs from I.C.I. Illuminant C must be reasonably similar to it, and in order to satisfy this requirement the ratio of spectral transmission of the filter at wave length 670 mμ to that of 700 mμ shall be 0.9 or more.

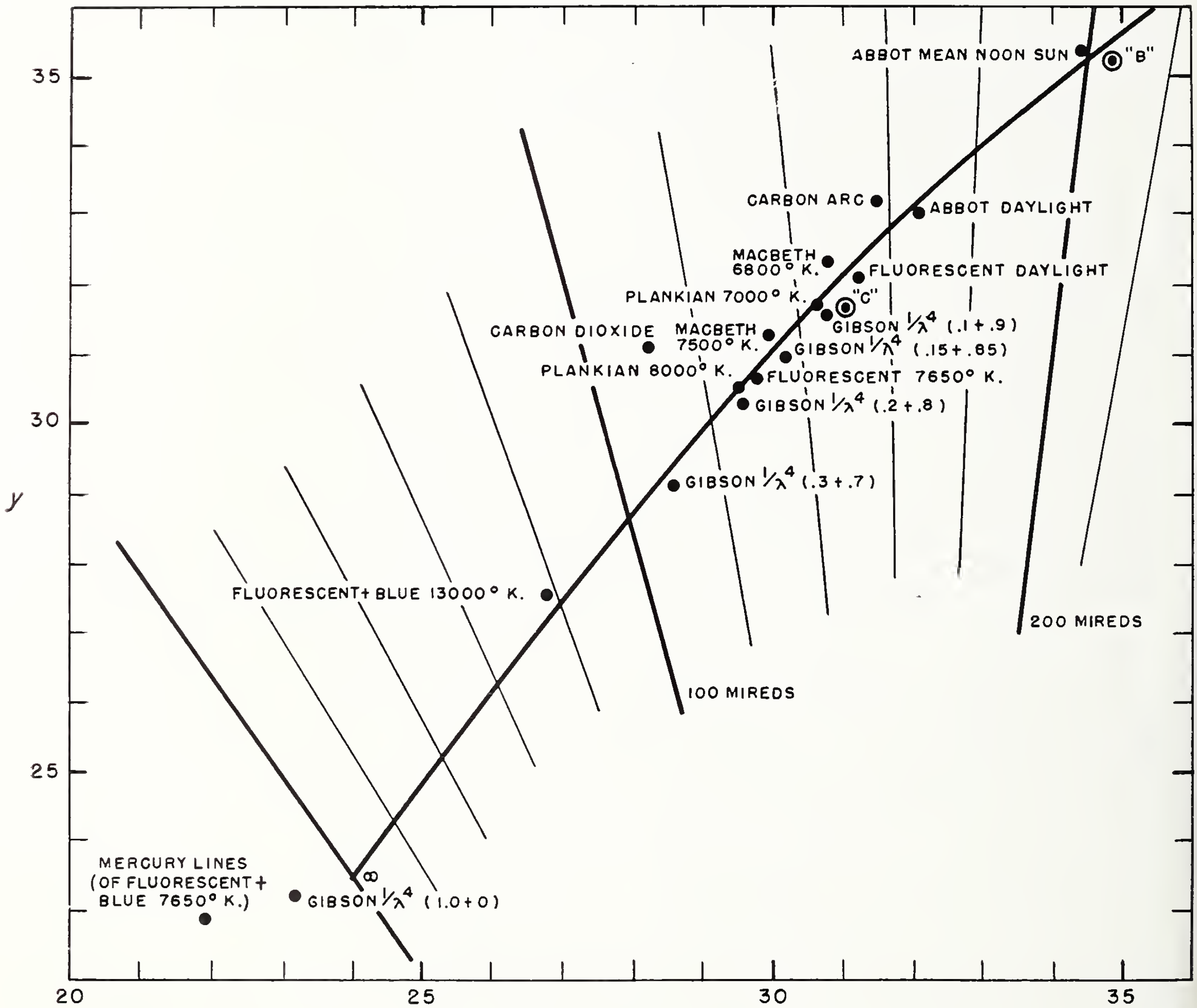

FIGURE 46.—A portion of the I.C.I. (x, y)-diagram showing the Planckian locus crossed by iso-temperature lines from 0 to 200 microreciprocal degrees (mireds). This covers the color-temperature range from I.C.I. "B" illuminant (representative of average sunlight) at 4,800° K (208 mireds) to the bluest of skies, 25,000° K and above (40 mireds or less). Actual and theoretical illuminants studied are shown on this diagram.

Figure 45 illustrates curves of relative spectral energy distributions supplied by cooperating laboratories for a number of actual and theoretical illuminants considered before selecting a filter-incandescent lamp as the most satisfactory available substitute for daylight. Specifications in terms of color temperature, shown in figure 46, may be meaningless unless the energy distribution of the light is known. Curves for the few daylight measurements available in 1938 are shown, curves for I. C. I. Illuminants B and C, theoretical curves of Planckian distributions in the color temperature range 6,500° K to 8,000° K, and curves for Macbeth filter-incandescent lamp combinations at 6,800° K and 7,500° K, for Trutint filters, a special high temperature carbon arc (about 6,350° K), carbon dioxide (about 9,000° K), and fluorescent daylight at 6,500° K. Additional measurements at several color temperatures made in 1939 by Taylor and Kerr (*72*) are shown in figure 47, also a series of theoretical daylight curves derived by Gibson (*17*).

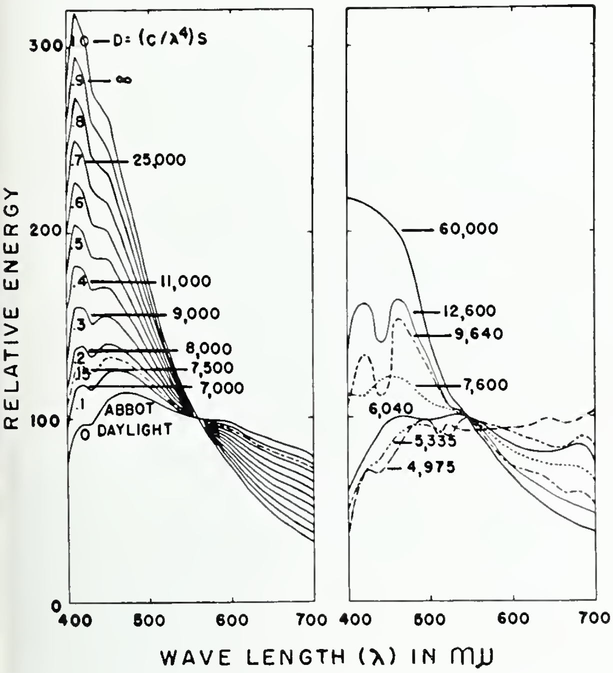

FIGURE 47.—Theoretical daylight curves derived by Gibson from different proportions of Abbot sun-outside-atmosphere and skylight calculated by use of inverse λ^4 scattering relation, and curves of daylight measurements made in Cleveland in 1939 by Taylor and Kerr (*72*).

The energy curve for the carbon arc shown is a reasonably good match for sunlight, but even this high temperature arc gives a color temperature that is too low. In addition to this color criticism, flicker and short carbon life are disadvantages of this type of unit, just as heat and high-power consumption are disadvantages of the lamp and filter unit.

Because fluorescent daylight is so widely used for purposes of general illumination, special caution should be given concerning its use in color grading. Because fluorescent light can be provided in units to give a large source of relatively low brightness with little heat and good diffusion, it would be ideal to use if its color characteristics were such as to make it a satisfactory substitute for daylight. But, fine as it is for other purposes, it does not make a good daylight substitute for general color grading work. In the grading of processed foods, for example, experience shows that beets, plums, grapes, and many other reds or purplish reds cannot be properly graded under fluorescent light. As illustrated in figure 45, fluorescent light is deficient at both the red and blue ends of the spectrum.

For cotton classification, it was fair when provided in special units at high-color temperature, but it was not really good even with these specially constructed units. Classers said they *could* learn to class under it, but it slowed up their judgments, and made them less sure of themselves. They did not like it—even in a specially built unit at 7,650° K—as well as the Macbeth 7,500° K unit. The fact that fluorescent daylight, without the addition of pink, has been found bad for use over cafeteria counters, in meat markets, and in tobacco display cases is some indication of the fact that it distorts daylight colors in a number of color ranges. For color matching, where color differences are more important than the daylight color of samples, its use may be satisfactory, but it cannot be installed without test for work in color grading, particularly where daylight color of the samples is important.

Good artificial daylighting, like good air conditioning, must fulfill two requirements. Good air conditioning concerns humidity as well as temperature control; good artificial daylighting concerns energy distribution as well as color control. With only one factor controlled, either air conditioning or artificial daylighting may be quite unsatisfactory for some purposes. After investigations that have involved several years study, it has been found that artificial daylight supplied by passing incandescent tungsten light through glass filters equivalent to Corning No. 590, in units properly designed for specific grading work, gives the most satisfactory technical and practical substitute for daylight of the desired color characteristics that is available today.

For some grading work large units are needed, for other work, especially that which can be done on a table in fixed areas, much smaller (and therefore less expensive) units may be used. The cotton-classing unit, developed on the basis of work done with the special unit illustrated in figure 43, is about 7 feet long, 3 feet wide, and 2¼ feet high, and contains six 1,000-watt incandescent lamps, so that forced draft ventilation is necessary; a smaller unit, about 3 feet long, less than 1 foot wide, and 9 inches high, containing four 200-watt lamps, ventilated by natural draft (unless small fans are added) is used over grading tables in the grading of processed foods. Still other sizes and shapes of daylight units are available for small-area illumination.

COLOR-VISION TESTING

Before work begins on any color grading problem, the matter of possible "color-blindness" of inspectors

should be taken into consideration if grading errors are to be avoided.

The term color-blindness is an unfortunate misnomer, for actually it covers all types of deficiency in color vision (*37*), not merely that rare individual to whom the world appears only in various degrees of gray. Individuals who are color deficient often develop a keen recognition for small lightness differences, and may therefore estimate color differences for some time without suspecting that there is anything wrong with their color vision. But the more color-insensitive they are, the greater is the error when they make one. Since it is conservatively estimated that at least one male out of every ten is affected to some degree, it is important that every potential grader or inspector be examined for color-blindness. Most deficiencies are in recognition of green and red. It is seldom that blues and yellows are not recognized, and this should be kept in mind in those cases in which recognition of yellows and blues is all that is required.

Many authorities classify color vision in three main groups: Trichromats, those whose color vision is a function of three variables; dichromats, those whose color vision is a function of two variables; and monochromats, those whose color vision is a function of one variable only. Trichromats make light-dark, yellow-blue, and red-green discriminations; they may have normal color vision or they may have restricted color vision, in which case they are called anomalous trichromats. Dichromats make light-dark and either yellow-blue or red-green discriminations and are generally classified as protanopes, deuteranopes, and tritanopes. Some authors introduce a fourth term, tetartanopes, but the distinction between tritanopes and tetartanopes is more theoretical than practical. Tritanopia arises chiefly through diseases of the eye. Monochromats, the third class, are those whose color vision is a function of one variable only. Like tritanopes they are extremely rare, and their condition is generally ascribable to disease of the eye.

Individuals whose color vision is similar to the normal, but much more restricted in ability to distinguish small red-green differences (anomalous trichromats) are the hardest to test, yet they are often seriously handicapped for inspection or grading work. Such persons make their color discriminations with relative difficulty, and often "guess" correctly. The inexperienced examiner often thinks of this type as "color ignorant" and lets him by, particularly when the subject is able to name correctly the colors of spots that may be pointed out to him. But naming the hue is not the same thing as seeing the color as the normal does, nor will it allow an inspector to class properly.

Several chart tests can quickly indicate the worst cases of color-blindness. The Ishihara Tests for Color-Blindness (*32*) are simple to give and interpret. The Stilling's Plates (*30*) are well known. Both were reproduced in whole or in part in 1941 in this country because there was fear that the originals might no longer be available. Plates from both are included in what is known as the AO Test (*2*) published by the American Optical Company, and the Stillings charts in the Meyrowitz American Edition of Stillings (*69*). The fact that these tests have been widely reproduced is believed by some to have restricted their usefulness, but that depends to a great extent on how the test is given. All tests should be given under good daylight or satisfactory artificial daylight conditions. The tests should be given as rapidly as an individual observer can read; no time should be allowed for careful scrutiny. If, in addition to this, the order of plates is reversed, and certain other plates inserted, there is little possibility for an observer to fool the operator. The advantage with the Ishihara type plates is that both the normal and the color-blind read figures on most charts but the figures seen by the normal differ from those seen by the color-blind.

When the Rabkin Test (*64*) again becomes available in this country, it will undoubtedly be widely used, for to date it seems the best of the published chart types. A test now under construction by Hardy, Rand, and Rittler at the Knapp Memorial Laboratories of the Institute of Ophthalmology, Presbyterian Hospital (New York) will, when published, be better still; that is, if in publication the charts lose none of the effectiveness of the originals. These new tests are intended to discover blue-yellow as well as red-green cases of deficiency, and to discover the degree as well as the kind of deficiency.

Color-blindness studies such as those of Hardy, Rand, and Rittler at the Presbyterian Hospital, studies by Farnsworth at the United States Submarine Base at New London, and by Judd at the National Bureau of Standards are the outcome of work initiated by each but encouraged by the Color-Blindness Committee of the Inter-Society Color Council. Results published to date include a single judgment test for red-green discrimination developed by the committee as a whole (*28*) and two tests by Farnsworth that use Munsell standard colors as a basis (*13*). One of these, the Farnsworth Dichotomous Test, developed for testing applicants for the Submarine Service, is a very simple one that may be constructed in any laboratory if one understands the principle behind it and cannot obtain the test made up. It is quick to give, and cannot be learned; it is intended only to discover the worst cases. The other test, the Farnsworth-Munsell 100-hue test, is perhaps the best research test other than the anomaloscope that has yet been made generally available for exploring color-blindness. Under the anomaloscope test a subject is required to match a narrow band of wave lengths in the yellow region of the spectrum with narrow bands taken from the green and red regions of the spectrum, the proportions needed to make the match indicating the type and degree of color deficiency.

The Inter-Society Color Council has also had a committee working on a color-aptitude test, described by Dimmick (*10, 11*), and designed, as the name implies, to measure aptitude for color-matching work rather than to measure color deficiency. This test is useful for testing the color aptitude of prospective inspectors, graders, or color matchers. It measures the speed and accuracy of making color matches of small-color differences.

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